Review

Application of Femtosecond Laser in Ocular Surgery

Peili Hou, Yan Lu, Fen Ye, Wen Lan, Zhenping Huang*
Medical School of Nanjing University, Nanjing 210093, China

Abstract

The femtosecond laser is a type of laser that can produce pulses of light of extremely short duration. The application of femtosecond laser in surgery results in no thermal effect or shock wave, so that this laser is unlikely to cause tissue injuries outside the irradiation area of the laser beam. The femtosecond laser shows promising applications in refractive surgery and corneal transplantation due to its high precision and predictability. In this paper, we review the clinical application of the femtosecond laser in refractive surgery and corneal transplantation. (***Eye Science 2013; 28:103-107***)

Keywords: femtosecond laser; refractive surgery; cataract surgery; corneal transplantation

Mechanism and features of femtosecond laser

The femtosecond laser uses a type of near infrared light with a wavelength of 1053 nm, which yields the shortest pulse obtainable. The femtosecond laser produces extremely high instantaneous power and can focus on quite a limited area, smaller than a hair's breadth; therefore, the electromagnetic field strength substantially exceeds the interaction between atomic nuclei and surrounding electrons. In ophthalmology, the femtosecond laser rapidly focuses on tissue microstructures for a short time, ionizes corneal tissue, and forms corneal plasma. The electromagnetic field strength produced by plasma is many times higher than the interaction between atomic nuclei and surrounding electrons; consequently, microbubbles consisting primarily of CO_2 and H_2O gases are yielded by photofragmentation and thousands of these microbubbles are further connected by the laser pulse to incise tissues.

The femtosecond laser is characterized by ultrashort laser pulses and ultrahigh peak power. The tight focusing and nonlinear nature of the absorption make it possible to confine the absorption to the focal volume inside the bulk of the material without causing absorption at the surface. Therefore, the femtosecond laser can be applied to perform clear, highly localized cuts in biological samples[1,2]. Since photodisruption does not require a specific absorber target, it is potentially useful for cutting tissues at arbitrary locations in space, as long as the tissue path to the target location is reasonably transparent to the photodisrupting beam[3].

The femtosecond laser is extensively applied in refractive surgery and corneal transplantation due to its concentrated laser beam energy, precise spatial localization, and low incidence of thermal injuries, retinal traction and fundus ischemia, *etc*.[4].

Application of femtosecond laser in refractive surgery

Creation of a corneal flap for laser in situ keratomileusis (LASIK)

Creating a corneal flap is a key step in LASIK. The use of a mechanical microkeratome for this process can cause button-holing of the flap or a free flap, *etc*. It can also lead to a corneal flap with a thin central cornea and a thick peripheral cornea. In contrast, the femtosecond laser is able to create a thinner, flatter, and more even corneal flap.

The thickness of the obtained corneal flap fluctuates over a limited range. Fusheng Li et al[5]. compared the corneal thickness after creating corneal flaps in 50 subjects (100 eyes) with either a Ziemer femtosecond laser or a Moria M2 mechanical microkeratome. The central thickness of the corneal flap was significantly thinner for the laser group postoperatively, as was the thickness of the corneal flap measured from each peripheral point to the central

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* **Corresponding author**: Zhenping Huang, E-mail: hzp19633@hotmail.com

cornea. The estimated value was significantly lower in the laser group than in the microkeratome group. Yongqiong Lou et al[6]. obtained similar findings. These results indicate that flap creation using the femtosecond laser is precise and predictable and yields desirable visual acuity. Ying Qi et al[7]. also compared the postoperative visual acuity after creating corneal flaps using femtosecond laser and microkeratome and found no differences in uncorrected visual acuity and diopter between the two groups at 1 and 3 months postoperatively. High order aberrations, except three-leaf-clover aberration, were significantly increased in the microkeratome group compared to the femtosecond laser group.

When compared with traditional LASIK, flap creation by a femtosecond laser for LASIK enhances postoperative visual acuity and reduces the postoperative complications caused by flap creation with a microkeratome. Thus, flap creation is safer and more efficacious when performed with a femtosecond laser than with a microkeratome.

Femtosecond laser corneal refractive surgery

The entire procedure for intrastromal laser keratomileusis (ILK), also known as femtosecond lenticule extraction (FLK), beginning with creation of the corneal flap to creation of a lenticule, can be accomplished independently with a femtosecond laser. At present, two approaches are used to create a lenticule: one method is small incision lenticule extraction (SMILE), which initially creates a corneal lenticule using the femtosecond laser, makes a cut around corneal limbus, inserts a separator via this incision, and performs the lenticule extraction[8]. The other approach is femtosecond lenticule extraction (FLEx), which utilizes a femtosecond laser to create the corneal flap, separates and extracts the lenticule from the corneal bed using a forceps, and manually restores the corneal flap. ILK creates any shape of incision with smooth and clear incisional margins, yields small postoperative aberration, and causes no thermal injuries to surrounding tissues.

The accuracy of the femtosecond laser largely depends on the intraoperative corneal environment and tissue characteristics, which can lead to relatively poor surgical stability and precision. However, both FLEX and SMILE are relatively stable and safe techniques. The extraction of the lenticule by the femtosecond laser maintains an intact epithelial layer; therefore, less postoperative complications occur and the lenticule incisions have even thickness and clear margins. SMILE preserves the corneal structure, causes fewer postoperative corneal irritations, and stabilizes the mechanical properties of the cornea, thereby realizing the goal of minimally invasive surgery.

Astigmatism correction by femtosecond laser

High astigmatism is a vital factor affecting visual acuity. Irregular astigmatism after corneal transplantation influences the postoperative visual acuity. Femtosecond laser-assisted corneal resection or wedge-shaped resection provides a novel treatment for astigmatism. Bahar I et al[9]. performed artificial and femtosecond laser-assisted keratotomy on patients who had corneal astigmatism following corneal transplantation and found that laser-assisted keratotomy was safer, more accurate, and led to less postoperative complications than artificial keratotomy.

Application of femtosecond laser in cataract surgery

In addition to its use in flap creation for LASIK, femtosecond laser can also be applied in cataract surgery, and has shown multiple advantages including high accuracy, central capsulorhexis, and good repeatability of capsulorhexis, *etc.* Bali et al[10]. employed a femtosecond laser for creation of a transparent corneal incision, anterior capsule resection, and fragmentation of the lens nucleus, and then performed IOL implantation after phacoemulsification. Intraoperative and postoperative complications did not differ from those experienced following traditional cataract surgery. Ecsedy et al[11]. statistically compared the influence of femtosecond laser-mediated cataract surgery and traditional cataract surgery on macular thickness and volume and on measured macular and retinal thickness by OCT at 1 week and 1 month postoperatively; no statistically significant difference was noted between the two surgical techniques, indicating that femtosecond laser was safe and induced no retinal injury. Shveta J et al[12]. adopted the femtosecond laser to conduct cataract surgery combined with vitrectomy and found no postoperative complications during and after the operation. The patients showed transparent corneas, the IOL

was in the proper position, and the cornea was flattened. Following surgery, the patients were not required to stay strictly in a certain position. This technique also reduced the difficulty in performing phacoemulsification after vitrectomy. Femtosecond laser cataract surgery has high safety and accuracy and yields desirable postoperative efficacy. Therefore, it is likely to become more widely applied in cataract surgery.

Creating a corneal graft by cutting the cornea during corneal transplantation

Corneal transplantation remains the primary treatment against corneal diseases. However, the quantity of donor corneas is quite limited and the incidence of rejection responses is relatively high, which hampers the success of this transplantation. The femtosecond laser provides a novel approach for corneal transplantation due to its accuracy and predictability. More importantly, the femtosecond laser can create a corneal lamella of any shape and with an even thickness. The femtosecond laser can also precisely create a corneal flap. Previous research found that the surface of the cornea treated by a femtosecond laser was smooth and regular. The femtosecond laser can also be applied when performing corneal cutting at a depth of 400 μm in thickened corneas with edema and produces a smooth margin.

Application of the femtosecond laser in lamellar keratoplasty

Lamellar keratoplasty lowers the incidence of postoperative rejection since it leaves the recipient corneal endothelial cells untouched. Furthermore, lamellar keratoplasty reduces the incidence of surgical complications and improves patients' postoperative visual acuity. Femtosecond laser-assisted lamellar keratoplasty procedures include femtosecond laser-assisted anterior lamellar keratoplasty (FALK), femtosecond laser-assisted deep anterior lamellar keratoplasty (FDALK), and femtosecond laser-assisted endothelial keratoplasty (FLEK). FALK, as a novel technique for corneal transplantation, can be applied in the treatment of patients with lesions in the anterior corneal stroma, such as corneal surface scars and nutrition disorders in anterior corneal stroma, *etc.* Femtosecond laser-assisted lamellar keratoplasty differs from traditional keratoplasty as cutting can be performed at an accurate depth and range. The diameter and thickness of the cuts rely on the depth of stromal infiltration, as measured by anterior OCT. Generally, the diameter of the donor corneal graft is 0.1 mm larger than that of recipient. The characteristics and edema of the donor corneal graft usually require an increase in the cutting thickness of 20% . Rapid and sound healing of corneal grafts avoids the procedure of suturing. Consequently, the patients undergoing FALK showed fast recovery, low astigmatism, and few complications.

Prior to FALK, the residual scars on the stromal bed must be cut by laser. For deep stromal scars, FDALK should be performed for patients with keratoconus and keratectasia by cutting vertical, mushroom, or Z-shaped corneal limbus wounds. Donor corneal grafts with thicknesses of 70–100 μm have been sutured to the residual stromal bed of the recipient. Femtosecond laser cutting yields a smooth stromal surface[16]. A previous study reported that the best corrected visual acuity in patients with FLEK was worse than that seen in those receiving Descemet stripping and automated endothelial keratoplasty (DSAEK). The quality of cutting might be improved by adjusting the mode and energy of femtosecond laser[17].

A new generation of femtosecond lasers has high frequency and reduces corneal injuries since frequency and energy are conversely correlated. Thus, the femtosecond laser can achieve good clinical efficacy by enhancing the precision of cutting. Wenbo Hou et al[18]. performed FDALK in rabbit eyes placed on a 3D-platform controlled by concentric cycle scan program and precisely located the femtosecond laser at various energies in the deep corneal lamella, performing the laser cutting as the platform moved. The smoothest surface was created at a speed of 200 μm s^{-1} and apulse energy of 4.4 μJ. The femtosecond laser yielded a smooth and regular cutting surface. Luca B et al[19]. analyzed the technique of DALK, first creating a tunnel at a slope of 30° inside the stroma to allow gas infusion and then using the femtosecond laser at a frequency of 60 Hz to create a flap and mushroom-shaped incision at the lamella 100 μm from the thinnest corneal point. Subsequently, he ex-

tracted the flap and infused gas into the stromal tunnel, forming large bubbles. The results confirmed that this technique can be highly standardized, lowers the incidence of intraoperative and postoperative complications, and yields good visual acuity following keratoplasty.

The femtosecond laser has also been applied to DLEK, which is mainly performed in patients with a normal anterior corneal stroma and diseased corneal endothelia, such as occurs with bullous keratopathy and Fuchs corneal dystrophy, *etc.* Two surgical techniques are available: DELK under a corneal flap and DELK under a sclerocorneal pocket incision. The aim of DLEK is to remove the Descemet and endothelia and to attach the donor endothelia with residual stroma to the endothelial surface of diseased eyes. DLEK is a relatively difficult operation and frequently leads to graft dislocation. Femtosecond laser-assisted DLEK allows cutting at the same diameter and depth, which not only decreases the surgical difficulty, but also guarantees tight closure between the graft and the graft bed, which prevents graft dislocation. Cheng et al. performed femtosecond laser-assisted DLEK in patients with bullous keratopathy and found that postoperative visual acuity was well recovered[20].

Application of femtosecond laser in penetrating keratoplasty

Penetrating keratoplasty (PK) refers to the proper placement of a donor graft of suitable size in corresponding sites of the recipient. The vertical wound must be sutured, which prolongs the healing time. In 2003, Busin invented an artificial technique for cutting the donor graft and achieved relatively desirable visual acuity postoperatively[21]. This technique was further modified with a femtosecond laser. Femtosecond laser-assisted keratoplasty mainly yields cap-, half-cap-, wedge-, mushroom-, Z- and tree-shaped wounds[14,22-24], which enlarge the surface area of the graft and enhance the connection and stability of the transplant joint. Romesb I et al[25]. compared the clinical efficacy of drilling a ring-hole by artificial operation and by a femtosecond laser and then looked for differences in intraocular pressure, endothelial cell injury, wound shape, and wound healing between these two techniques. They found that the patients in the femtosecond laser groups showed smaller IOP fluctuation, less endothelial cell damage, and faster wound healing.

During femtosecond laser-assisted keratoplasty, the diameter of the posterior surface of the grafts can be adjusted for a variety of purposes. For patients with endothelial cell deficiency, a cap-shaped wound enlarges the posterior surface area and increases the quantity of transplanted endothelial cells. For those with keratoconus, a mushroom-shaped incision can be created to minimize the posterior surface area, preserve the number of endothelial cells of autograft as much as possible, and reduce the incidence of rejection. The cap-shaped wound has been regarded as the most stable incision[22]. The purpose of wound suturing is to stabilize the position of graft rather than prevent leakage. Consequently, femtosecond laser-assisted PK needs fewer sutures and the stitches can be removed early. It also yields low astigmatism and relatively fast recovery of visual acuity.

Outlook

The femtosecond laser creates a smooth surface and avoids irregular anterior and posterior surfaces. Based on anterior OCT data, the femtosecond laser can be used to mediate corneal cutting and allows for consistency between cutting depth and estimated value. The femtosecond laser is also applicable to asymmetrical transplantation and creates non-geometric transplant grafts. Currently, the femtosecond laser is mainly applied in flap creation for LASIK. However, diseased corneas, corneal edema, opacity, and especially anomalous corneal scars may affect the laser energy and decrease the predictability of corneal cutting depth. The data related to laser index settings remain limited. In summary, the femtosecond laser indeed improves surgical precision, stability, and predictability and yields desirable postoperative visual acuity. Therefore, the femtosecond laser has a broad application in ocular surgery.

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