Simple Optical Configuration for Continuous Curvilinear Capsulorhexis

Hee Chul Lee

R&D Division, Lutronic Center, Goyang, Korea

Background and Objectives

The continuous curvilinear capsulorhexis (CCC) technique has many advantages, but it is a difficult technique to master. A femtosecond laser system for cataract surgery offers greater precision and reproducibility in opening the anterior capsule than the manual method. The proposed simple femtosecond laser system for CCC can be widely used, compared with the conventional system, due to its compact size and cost-effectiveness.

Materials and Methods

Ex vivo testing of the designed simple optical system for CCC in porcine eyes was performed. A laser irradiated the porcine eyes with a 10 μm spot size and energy of 10 μJ .

Results

CCC was successfully performed for diameters of 5 mm, 5.5 mm, and 6 mm by a newly designed simple optical system. Sliding the anterior capsule with tweezers to confirm the quality of the incision showed that the operation was successful.

Conclusion

Compact and simple laser system showed to have good performance. As shown, CCC can be widely adopted for its precision and low cost.

Key words

Femtosecond laser; Cataract surgery; Optical design

Received October 24, 2016
Revised November 18, 2016
Accepted November 18, 2016

Correspondence

Hee Chul Lee
R&D Division, Lutronic Center, 219 Goyang 10534,
Korea
Tel.: +82-70-4714-6104
Fax: +82-31-901-3440
E-mail: hclee@lutronic.com

© Korean Society for Laser Medicine and Surgery

© This is an open access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

INTRODUCTION

The number of cataract operations is continuously increasing.^{1,2} Cataract surgery depends solely on the surgeon's surgical skills when manually implanting an artificial lens.²⁻⁶ The continuous curvilinear capsulorhexis (CCC) technique has many advantages but is difficult to learn. Recently, a femtosecond laser system has been developed for cataract surgery; this system automatically executes corneal and anterior chamber incisions and fragments the crystalline lens.^{1,7} Because the laser must irradiate both the corneal and crystalline lenses, the focal plane must be able to move 7 to 8 mm within the eye. Moreover, when the crystalline lens is fragmented, the numerical aperture (NA) must be changed because of the size of the iris; this in turn increases the complexity of the optical system configuration (US Patent 20110196350 A1 and US Patent 20110028951 A1). Consequently, this laser system is prohibitive for private hospitals to acquire because it is highly expensive and complex.

Unfortunately, successful creation of the CCC is regarded by surgeons in training as one of the most challenging steps of cataract surgery, and considerable variation exists between experienced surgeons.^{8,9} However, capsulotomies created by using femtosecond laser systems are more accurate in size than those created manually.^{1,5} The purpose of this study is to introduce a femtosecond laser treatment device that realizes a simple and inexpensive optical configuration for CCC, which can help relieve the burden for surgeons.

MATERIALS AND METHODS

Human eye and objective lens

1) Human eye

The Navarro model is chosen as a schematic of the human eye, and its specifications are shown in Fig. 1.⁹ Although the outer surface of the cornea typically requires an aspheric coefficient, it is ignored in this design. This is because the eye interface (EI) lens (a lens that contacts the cornea and provides focused beams with less distortion and aberration during propagation within the eye) is in contact with the cornea. The eye must be fixed during cataract surgery; this is accomplished by the EI lens, the detailed structure of which is shown in Fig. 2.

2) Objective lens

Current surgical systems employ a 10- μm spot size for the anterior capsule incision or fragmentation of the crystalline lens.¹⁰ Precisely moving the focal plane to create an incision in the anterior capsule with a thickness of only 10 to 20 μm is extremely difficult. The thickness depends on the position of the anterior capsule and is different for every human eye. The ability to move the focal point in the Z-direction is also crucial given the physical differences in the length of anterior chamber. Although the objective lens and wedge prism can be moved spatially, doing so is more complicated than in the optical method. Eventually, the crystalline lens is phacoemulsified to insert the artificial lens after fragmentation so that laser irradiation of

Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic
OBJ	Standard	Infinity	Infinity		Infinity	0.00000
STO	Standard	Infinity	25.00000		4.00000	0.00000
2*	Standard	-13.32730	8.85145	N-SF11	10.00000 U	0.00000
3*	Standard	-20.40385	3.23707		12.50000 U	0.00000
4*	Standard	-98.65794	6.99254	N-SF11	15.00000 U	0.00000
5*	Standard	-43.97753	0.10000		15.00000 U	0.00000
6*	Standard	187.36302	3.50000	N-SF11	15.00000 U	0.00000
7*	Standard	-143.38936	1.50603		15.00000 U	0.00000
8*	Standard	56.73067	4.12216	N-SF11	15.00000 U	0.00000
9*	Standard	Infinity	31.60000		15.00000 U	0.00000
10*	Standard	Eye Interface	-69.80498	F_SILICA	5.00000 U	0.00000
11*	Standard	7.72000	0.00000		5.00000 U	0.00000
12	Standard	Cornea	7.72000	1.38,50.2	3.31016	0.00000
13	Standard	Aqueous	6.50000	1.34,50.2	3.24915	-0.60000
14+	Standard	Pupil	Infinity	1.34,50.2	3.10470	0.00000
15	Standard	Anterior Caps..	10.20000	1.40,0.0	3.02586	0.00000
16	Standard	Crystalline l..	10.20000	1.41,46.5	3.02494	0.00000
IMA	Standard	Infinity	-		3.00396	0.00000

Fig. 1. Captured image from Zemax Lens Editor program showing objective lens and human eye.

Fig. 2. Schematic of optical system for objective lens and human eye.

Fig. 3. Focused position and spot diagram for each incidence angle.

the crystalline lens does not cause problems. Therefore, an incision 200 μm below the anterior capsule is chosen in this study.

The effective focal length is 28.22 mm when the size of the incident beam on the objective lens is 8 mm, making the NA 0.14. When the beam is incident to the crystalline lens in an eye with the EI installed, the effective focal length becomes 30.32 mm, which reduces the NA to 0.13. The location of the entrance pupil was designed to be 25 mm from the first side of the objective lens. The optical system was designed by using Zemax software. The femtosecond laser used in this study has a wavelength of 1.034 μm and an optical pulse width of 400 fs, and does not require dispersion compensation. The focused positions and spot sizes within the crystalline lens are shown in Fig. 3 for various incidence angles. When the incident angles on the objective lens were 4.732° and -4.732° , the spots were formed at 2.5 mm and -2.5 mm, respectively. When the angle of incidence was increased to 0.476° , the spot position increased by a 0.25-mm equidistant interval. The size of the Airy disk was 9.56 μm , and the energy distribution for all spots existed within the Airy disk.

Application of wedge prism and focal point control

1) Application of wedge prism

The aim of this study is to achieve a simple and inexpensive optical system for CCC. Usually, a circular beam pattern requires a two-axis scanner, which is expensive

and difficult to control. Moreover, X and Y mirrors are placed at different locations along the beam path, resulting in pincushion distortion. Thus, a relatively low-cost wedge prism with the same central thickness and a different angle was chosen to achieve various diameter of CCC. Changing the wedge prism to adjust the diameter of the curvilinear pattern is inconvenient. However, in normal cataract surgery, the diameter of the CCC is 5 to 6 mm.^{2,10,11} Therefore, replacing the wedge prism should not be inconvenient. The overall structure and specifications of the optical parts are shown in Fig. 4 and 5, respectively. The optical system must be positioned in the center of the eye. Because a camera and an optical coherence tomography (OCT) device are helpful for locating the center of the eye, dichroic filters were considered, as shown in (Fig. 4). In particular, an OCT device is essential for correcting the incident position of the laser with high resolution because it provides information about the thickness of various structures including the cornea and anterior chamber.^{4,10,12,13} With wedge prism angles of 9.2° , 10.09° , and 10.97° , curvilinear patterns of 5, 5.5, and 6 mm, respectively, were obtained. In each case, an identical radius was produced when the wedge prism was rotated 360° .

2) Changing the focal length by using a beam expander

A beam expander (BE) is designed for a femtosecond laser with a beam size of 3 mm; by expanding the beam size to 8 mm with the BE, the beam is incident on the ob-

Fig. 4. Optical system configuration for continuous curvilinear capsulorhexis (CCC).

Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic
OBJ	Standard		Infinity	Infinity		0.00000	0.00000
1	Standard		Infinity	10.00000		1.50000	0.00000
2*	Standard		Infinity	5.00000	N-SF11	10.00000 U	0.00000
3*	Standard		13.34233	10.00000		7.50000 U	0.00000
4*	Standard		-39.06872	10.00000	N-BK7	8.00000 U	0.00000
5*	Standard		-27.11510	17.20000		10.00000 U	0.00000
6*	Standard		43.66262	10.00000	N-SF2	10.00000 U	0.00000
7	Standard		Infinity	30.00000		4.12347	0.00000
8	Coordinat..			0.00000	-	0.00000	
9*	Standard		Infinity	3.00000	BK7	20.00000 U	0.00000
10	Standard		Infinity	0.00000		7.33085	0.00000
11	Coordinat..			30.00000	-	0.00000	
12	Coordinat..			0.00000	-	0.00000	
13*	Standard		Infinity	3.00000	BK7	20.00000 U	0.00000
14	Standard		Infinity	0.00000		5.68064	0.00000
15	Coordinat..			30.00000	-	0.00000	
16*	Tilted	FRONT PRISM 1		5.00000	BK7	10.00000 U	
17*	Tilted	BACK PRISM 1		25.00000		10.00000 F	
18*	Standard		-13.32730	8.85145	N-SF11	10.00000 U	0.00000
19*	Standard		-20.40385	3.23707		12.50000 U	0.00000
20*	Standard		-98.65794	6.99254	N-SF11	15.00000 U	0.00000
21*	Standard		-43.97753	0.10000		15.00000 U	0.00000
22*	Standard		187.36302	3.50000	N-SF11	15.00000 U	0.00000
23*	Standard		-143.38936	1.50603		15.00000 U	0.00000
24*	Standard		56.73067	4.12216	N-SF11	15.00000 U	0.00000
25*	Standard		Infinity	31.60000		15.00000 U	0.00000
26*	Standard	Eye Interface	-69.80498	1.50000	F_SILICA	5.00000 U	0.00000
*	Standard		7.72000	0.00000		5.00000 U	0.00000
28	Standard	Cornea	7.72000	0.55000	1.38,50.2	3.24331	0.00000
29	Standard	Aqueous	6.50000	2.70000	1.34,50.2	3.18448	-0.60000
30+	Standard	Pupil	Infinity	0.00000	1.34,50.2	3.00000 U	0.00000
31	Standard	Anterior caps..	10.20000	1.0000E-002	1.40,0.0	2.99778	0.00000
32	Standard	Crystalline l..	10.20000	0.43621	1.41,46.5	2.99873	0.00000
IMA	Standard		Infinity	-		2.99739	0.00000

Fig. 5. Captured image from Zemax Lens Editor program showing wedge prism adopted in optical system for CCC.

jective lens. In addition, to optically move the focal length, the lens distance in the BE is moved to change the beam divergence. When the distance between the second and third lenses in the BE is 15.01 mm, the BE has an almost infinite focal length. This focal length can be changed by divergence of the input beam on the objective lens. Therefore, extension of the focal distance of the objective lens is required to increase the input beam divergence, which is realized by reducing the distance between the lenses to less than 15.01 mm. Conversely, increasing the distance between the lenses to more than 15.01 mm will shorten the focal length. For instance, when the distance between the lenses is changed from 13 to 16 mm, the effective focal distance of the BE is changed from -909.7 to 1840.2 mm. The extended focal length for the crystalline lens was 0.816 mm under the same conditions.

According to a chart of human eye size distribution, the thickness of the cornea is 0.5 to 0.6 mm and that of the anterior chamber is distributed from 2.2 to 4.7 mm. Therefore, the beam irradiation position for capsulorhexis is influenced more by differences in anterior chamber length than by differences in corneal thickness. Spot diagrams at 10 μm above and 200 μm below the anterior capsule are shown in Fig. 6. A slight degradation of optical quality was observed with an anterior chamber length of 4.7 mm, although the spot maintained a size of 10 μm , as shown in Fig. 7. The required lens distance for the BE, change in NA, and Airy disk size as a function of the anterior chamber length are listed in Table 1.

RESULTS

Test results of anterior capsule incision in porcine eye with crystalline lens

To evaluate the performance of the manufactured optical system, porcine eye samples were prepared. The corneal radius of curvature and thickness of the porcine eye are slightly larger than those of the human eye, although the anterior chamber is shallower. Therefore, the radius of curvature was modified. The simulated results, obtained by using the new EI lens for the porcine eye, are

Fig. 7. Point spread function for anterior chamber length of 4.7 mm.

Fig. 6. Spot diagram based on anterior chamber length. Point approximately 200 μm below the anterior capsule (*); point approximately 10 μm above the anterior capsule (#).

Table 1. Required lens distance for beam expander (BE), change in numerical aperture (NA), and Airy disk size based on anterior chamber length

Anterior chamber length		2.2 mm	3.45 mm	4.7 mm
Under 200 μm point	Lens distance for BE	18.6 mm	13.88 mm	8.9 mm
	Airy disk size	9.81 μm	9.56 μm	9.33 μm
	NA	0.127	0.131	0.134
Above 10 μm point	Lens distance for BE	19.5 mm	14.8 mm	9.9 mm
	Airy disk size	9.87 μm	9.62 μm	9.36 μm
	NA	0.126	0.13	0.133

shown in Fig. 8. The energy distribution at every spot size is within the 10- μ m diameter of the Airy disk. Fig. 9 shows the test results of CCC by using wedge prisms with diam-

eters of 5, 5.5, and 6 mm. The rotation speed of the wedge prism was selected with the following considerations. First, the size of the laser spot was set to 10 μ m with a

Fig. 8. Spot diagrams within porcine crystalline lens for diameters of 5, 5.5, and 6 mm.

Fig. 9. Incision and exfoliation tests of anterior capsule for porcine eyes with wedge prism diameters of 5, 5.5, and 6 mm.

3- μ m overlap. Second, the laser repetition rate was fixed at 100 kHz. Therefore, the interval time between pulses was 10 μ s, during which the laser moved 7 μ m. Third, movement of the focal distance was determined by the spot size and required rotation time for each radius. The pulse energy was fixed at 10 μ J for all tests. As shown in Fig. 9, the CCC for each was successful; sliding the anterior capsule slightly with tweezers to confirm the quality of the incision showed that the operation went smoothly.

DISCUSSION

A simple optical configuration for CCC that uses a wedge prism was designed with Zemax software and its performance was evaluated. According to the simulated results, the spot size on a human anterior capsule with a diameter of 5, 5.5, and 6 mm was sufficient for the incision. To confirm these results, CCC experiments were conducted with a porcine eye, using a modified EI lens. When the eye was irradiated with 10 μ J of energy, the CCC was successful at each diameter. A femtosecond laser for cataract surgery that automatically executes the corneal and anterior chamber incisions, and fragments the crystalline lens has been developed. The equipment is expensive and complex because the femtosecond laser source is very expensive, and for corneal incision, there must be a telecentric F- θ objective lens with a numerical aperture (NA) higher than 0.3. This F- θ lens must have a large diameter with a focal distance of several cm because the device holds the patient's eye. Additionally, it requires a beam expander (BE) with a large diameter to guide a large beam toward the F- θ lens. Finally, a precise three-axis scanner for a variety of patterns is necessary and expensive. In particular, because the laser has to be irradiated from the corneal to the crystalline lens, the focal plane must be able to move 7 mm to 8 mm within the eye. When we fragment the crystalline lens, because of the size of the iris, a large NA procedure involving the cornea is impossible. Therefore, the NA must be changed, making the optical system configuration more complicated. The purpose of this study is to introduce a femtosecond laser treatment device to realize a simple and inexpensive optical configuration for CCC, which can help relieve the burden for doctors. The simulated results suggest that the optical quality is degraded in the anterior chamber of a human eye with a length of 4.7 mm. Therefore, further studies will be needed to improve the optical quality.

REFERENCES

1. Nagy ZZ, Takacs AI, Filkorn T, Kránitz K, Gyenes A, Juhász É, et al. Complications of femtosecond laser-assisted cataract surgery. *J Cataract Refract Surg* 2014;40:20-8.
2. Reddy KP, Kandulla J, Auffarth GU. Effectiveness and safety of femtosecond laser-assisted lens fragmentation and anterior capsulotomy versus the manual technique in cataract surgery. *J Cataract Refract Surg* 2013;39:1297-306.
3. Donaldson KE, Braga-Mele R, Cabot F, Davidson R, Dhaliwal DK, Hamilton R, et al. Femtosecond laser-assisted cataract surgery. *J Cataract Refract Surg* 2013;39:1753-63.
4. Palanker D, Friedman NJ, Blumenkranz MS, Schuele G, Andersen D, Marcellino G, et al. Cataract surgery with OCT-guided femtosecond laser. Conference Paper, Bio-Optics: Design and Application, Monterey, California, United States, 2011 April;4-6.
5. Kránitz K, Takacs A, Miháltz K, Kovács I, Knorz MC, Nagy ZZ. Femtosecond laser capsulotomy and manual continuous curvilinear capsulorhexis parameters and their effects on intraocular lens centration. *J Refract Surg* 2011;27:558-63.
6. Ruggiero J, Keller C, Porco T, Naseri A, Sretavan DW. Rabbit models for continuous curvilinear capsulorhexis instruction. *J Cataract Refract Surg* 2012;38:1266-70.
7. Karavitis M. Refractive cataract surgery with the LenSx laser. Conference Paper, Frontiers in Optics, Rochester, New York, United States, October 24-8, 2010.
8. Navarro R, Santamaría J, Bescós J. Accommodation-dependent model of the human eye with aspherics. *J Opt Soc Am A* 1985;2:1273-81.
9. Friedman NJ, Palanker DV, Schuele G, Andersen D, Marcellino G, Seibel BS, et al. Femtosecond laser capsulotomy. *J Cataract Refract Surg* 2011;37:1189-98.
10. Navarro R, Santamaría J, Bescós J. Accommodation-dependent model of the human eye with aspherics. *J Opt Soc Am A* 1985;2:1273-81.
11. Friedman NJ, Palanker DV, Schuele G, Andersen D, Marcellino G, Seibel BS, et al. Femtosecond laser capsulotomy. *J Cataract Refract Surg* 2011;37:1189-98.
12. Chang JS, Chen IN, Chan WM, Ng JC, Chan VK, Law AK. Initial evaluation of a femtosecond laser system in cataract surgery. *J Cataract Refract Surg* 2014;40:29-36.
13. Ortiz S, Pérez-Merino P, Durán S, Velasco-Ocana M, Birkenfeld J, de Castro A, et al. Full OCT anterior segment biometry: an application in cataract surgery. *Biomed Opt Express* 2013;4:387-96.