

Imaging and investigating the effects of incision angle of clear corneal cataract surgery with optical coherence tomography

Bin Rao^{1,3}, Jun Zhang³, Mehran Taban⁴, Peter J. McDonnell⁵ and Zhongping Chen^{1,2,3}

Department of Electrical and Computer Engineering¹, Department of Biomedical Engineering², Beckman Laser Institute³, Department of Ophthalmology⁴, University of California Irvine, Irvine CA 92612-3010
Wilmer Ophthalmological Institute⁵, Johns Hopkins University, Baltimore, MD 21287-9278
zchen@bli.uci.edu

Abstract: Effects of incision angle in construction of clear corneal cataract incision are studied with optical coherence tomography (OCT). A stable incision angle range is found to be existent for single-planed, clear corneal cataract incisions. When well pressurized, incision angles within this stable range result in well-apposed incision edges that resist gapping while incision angles falling outside this range have a larger tendency for wound leakage. It is also shown that a two-planed incision can effectively expand the stable range. For incision angles outside the stable range, the farther the incision angle is away from stable range, the larger the gap between incision wound edges when well pressurized. These findings emphasize the significance of incision construction to the self-sealing property of clear corneal cataract incisions. Finally, we demonstrate that OCT could be an effective modality for imaging and monitoring corneal surgery.

©2003 Optical Society of America

OCIS codes: (170.4500) Optical Coherence Tomography; (170.4460) Ophthalmic Optics; (170.4470) Ophthalmology.

References and Links

1. Eric J.Linebarger, David R.Hardten, Gaurav K.Shah and Richard L.Lindstrom, "Phacoemulsification and Modern Cataract Surgery," *Survey of Ophthalmology* **44**, 123-147 (1999).
2. Norregaard JC, Thoning B, Bernth-Petersen P, et al, "Risk of endophthalmitis after cataract surgery: results from the international Cataract Surgery Outcomes Study," *Br J Ophthalmol* **81**, 102-106(1997).
3. Somani S, Grinbaum A, Slomovic AR, "Postoperative endophthalmitis: incidence, predisposing surgery, clinical course and outcome," *Can J Ophthalmol* **32**, 303-310(1997).
4. Aaberg TM Jr, Flynn HW Jr, Schiffman J, Newton J, "Nosocomial acute-onset postoperative survey: a 10-year review of incidence and outcomes," *Ophthalmology* **105**, 1004-1010(1998).
5. Morlet N, Gatus B, Coroneo M, "Patterns of peri-operative prophylaxis for cataract surgery: a survey of Australian ophthalmologists," *Aust NZJ Ophthalmol* **26**, 5-12(1998).
6. Thomas A.Ciulla, Michael B.Starr, Samuel Masket, "Bacterial Endophthalmitis Prophylaxis for Cataract Surgery," *Ophthalmology* **109**, 13-24(2002).
7. Christopher N.Ta, Peter R.Egbert, Kuldev Singh, Erin M.Shriver, Mark S.Blumenkranz, Herminia Mino de Kaspar, "Prospective Randomized Comparison of 3-Day versus 1-Hour Preoperative Ofloxacin Prophylaxis for Cataract Surgery," *Ophthalmology* **109**, 2036-2041(2002).
8. Yasunori Nagaki, Seiji Hayaska, Chiharu Kadoi, et al, "Bacterial endophthalmitis after small-incision cataract surgery," *J Cataract Refract Surg* **29**, 20-26(2003).
9. Shingleton BJ, Wadhvani RA, et al, "Evaluation of intraocular pressure in the immediate period after phacoemulsification," *J Cataract Refract Surg* **27**, 1709-1710(2001)
10. Percicot CL, Schnell CR, et al, "Continuous intraocular pressure measurement by telemetry in alpha-chymotrypsin-induced glaucoma model in the rabbit: Effects of timolol, dorzolamide, and epinephrine," *J Pharmacol Toxicol Methods* **36**, 223-228(1996)
11. Peter J. McDonnell, Mehran Taban, et al, "Dynamic Morphology of Clear Corneal Cataract Incisions," *Ophthalmology* **110**, 2342-2348(2003).
12. Brett E.Bouma and Guillermo J.Tearney, *Handbook of optical coherence tomography* (Marcel Dekker 2001).

13. Hongwu Ren, Zhihua Ding, Yonghua Zhao, Jianjun Miao, Nelson JS, Zhongping Chen, "Phase-resolved functional optical coherence tomography: simultaneous imaging of in situ tissue structure, blood flow velocity, standard deviation, birefringence, and Stokes vectors in human skin," *Optics Letters* **27**, 1702-1704(2002).
 14. Jue B, Maurice DM, et al, "The mechanical properties of the rabbit and human cornea," *J. Biomechanics* **19**, 847-853(1986).
 15. Hoeltzel DA, Atman P, et al, "Strip extensometry for comparison of the mechanical response of bovine, rabbit, and human corneas," *J Biomechanical Eng* **114**, 202-215(1992).
 16. Schmitz S, Dick HB, Krummenauer F, Pfeiffer N, "Endophthalmitis in cataract surgery: results of a German survey," *Ophthalmology* **106**, 1869-1877(1999).
-

1. Introduction

Cataract surgery is one of the major advances in modern medicine. It has become one of the safest, most successful and most common outpatient procedures and takes as little as ten minutes to perform. The current success of cataract surgery can be attributed to the technological advances that have occurred in the last decade. This includes the evolution of phacoemulsification handpieces, advances in anesthesia, small, self-sealing clear corneal incisions, viscoelastics, capsulorhexis, hydrodissection, hydrodelineation, and advances in intraocular lens (IOL) development [1]. More and more surgeons prefer clear corneal incisions instead of scleral-tunnel incisions in the United States and Europe.

Postoperative endophthalmitis has a low incidence of between 0.08% and 0.3% following cataract surgery. However, it remains a devastating complication with high visual mortality [2-5]. Some studies have investigated the source of bacterial infection by comparing intraocular isolates with isolates from tear film, eye-lid and adnexa [6]. There is evidence that surface floras routinely gain access to the anterior chamber during cataract surgery. Several prophylactic strategies for suppressing both the number and growth of organisms that enter the eye have been employed clinically [6,7]. However, some of them have no clear supporting evidence of benefit and cost effectiveness. Endophthalmitis prevention is very difficult to study because of its low incidence and other potentially complicating factors. A prophylactic agent, which may be capable of reducing ocular contamination during surgery, may fail to show clinical benefit in the presence of incisions that are not hermetically sealed [8]. Clinically, the self-sealing property is judged by a simple procedure. The clear cornea cataract incision is inflated with balanced salt solution. Then by applying pressure on the anterior surface of cornea, the wound leakage can be checked. In case of leakage, balanced salt solution is injected into the wound through a cannula, allowing the swollen stroma to appose the wound edges and set up a "barrier" for fluid flow. Such clinical procedures assume that the eye will be well pressurized during the early postoperative period.

However, such assumption is doubtful. Postoperative intraocular pressure (IOP) can frequently drop below 5 mmHg [9], and large fluctuation of IOP occurs in response to blinking [10]. To find out the mechanism of postoperative endophthalmitis, we studied the possibility of surface fluid imbibition with India ink that was applied to the corneal surface [11]. We assume surface fluid will infiltrate more easily and hence can reach a deeper position in wounds than India ink. By checking histological sections of fixed tissue, we proved the penetration of surface fluid into incision wounds during periods of intraocular pressure fluctuation. The dynamic morphological changes of clear corneal cataract incisions were studied with a functional OCT (f-OCT) instrument. The 90° clear corneal cataract incision wound behaved contrary to the 20° self-sealing cataract incision wound under IOP fluctuation.

Although incision angle is a key factor for clear corneal cataract incision construction, to our knowledge, the selection of incision angle is usually based on surgeons' experiences. Thus, it is of great interest to study the incision angle factor in construction of clear corneal cataract incisions.

2. Materials and methods

2.1 Tissue preparing and surgical procedure

Intact human globes 1-4 days postmortem were bought from the San Diego Eye Bank. Freshly enucleated New Zealand white rabbit eyes were bought from a local abattoir. 22 freshly enucleated rabbit eyes and 17 human globes were used in these series of experiments. The large quantity required is in part due to the difficulty of constructing incisions of different angles without the aid of vitreolastic material used in conventional clear corneal cataract surgeries.

All globes were kept at 4°C in a moist chamber. Globes were placed in a specially designed globe holder and the eyes were oriented so that the temporal cornea was placed at the 12-o'clock position under the aid of microscope. A 23-gauge needle was inserted through the limbus at the 6 o'clock position, 180 degrees away from the site for the clear corneal incision. Intraocular pressure was set by adjusting the height of the bottle of balanced salt solution connected to the 23-gauge needle with intravenous tubing.

Clear corneal incisions were created using a 3.0 mm disposable keratome (Alcon, Forth Worth, TX) under microscopic visualization. Incision tunnel lengths were then varied from 2.0 to 2.5 mm. In order to study the effects of different incision angles on human corneas, temporal corneal incisions were created with the same keratome blade oriented at different angles to the corneal surface. The exact incision angle was measured with an OCT image. The freshly enucleated rabbit eyes underwent surgery similar to that of human globes for the same purpose.

2.2 Optical coherence tomography

OCT provides the capability of non-invasively visualizing the dynamic morphological changes of clear corneal cataract incisions. This non-invasive imaging technology takes advantage of the short coherence length of a broadband optical source to pick up the reflected optical signals from sites of different depths by scanning the group delay of the reference beam in a low coherence interferometer. Heterodyne detection method gives rise to a high signal to noise ratio and large dynamic range image. The axial resolution of OCT can be as small as $0.44\lambda^2/\delta\lambda$, in which λ is center wavelength and $\delta\lambda$ is the bandwidth of partially coherent optical source. The transverse resolution is the same as conventional optical microscopy and is determined by the focusing properties of an optical beam. The transverse resolution is $4\lambda f/(\pi d)$, in which d is the spot size on the objective lens and f is its focal length. The principle of OCT has been described in detail [12].

In our experiment, a phase-resolved f-OCT instrument [13] was used for imaging dynamic morphology of incision wounds. Figure 1 shows a schematic f-OCT setup for our experiment. Essentially, it is a 2x2 fiber coupler-based Michelson interferometer with two beams, a reference beam linked to a rapid scanning optical delay line and a sample beam collimated and focused on the biological tissue. Light from a broadband, low-coherence optical source with a center wavelength of 1300 nm and bandwidth of 80 nm is coupled into a 2x2 fiber coupler based interferometer and then split into two beams. The reason the 1300 nm center wavelength optical source was chosen instead of 800 nm is that the stronger back-scattering light from corneas permits better image quality in 1300 nm center wavelength. The reflected light from both the reference beam and the sample beam are combined and returned to two input ports of the fiber coupler. When the rapid optical delay line is scanned along the whole imaging depth range, the photodiode detector is used to detect the combined light and produce dynamic fringe signals from which the reflection coefficients of sites at different depths are calculated. Transverse scanning is achieved by using a motorized scanning stage. OCT images with axial resolution of 9.3 μm and transverse resolution of 10 μm are displayed at a rate of 2.5 frames per second for a 2 mm transverse field view. It can be increased to 5 frames per second if the axial scanning frequency is doubled to 1 kHz.

To study the effect of incision angle in construction of clear corneal cataract incisions, f-OCT is used to monitor the incision wound stability when the IOP is fluctuated as frequently experienced in the first few hours of the postoperative period.

The eye was oriented under the imaging probe with the incision plane vertical to the transverse scanning optical beam. The sample beam was focused on the anterior segment of the eyes. As the OCT probe traversed the center of the corneal incision, a two-dimensional anterior chamber cross-sectional image was simultaneously acquired and displayed. All of the following OCT images and movies were acquired in the same way. For static images, 4 axial scans at each lateral point were performed to get an average structure image.

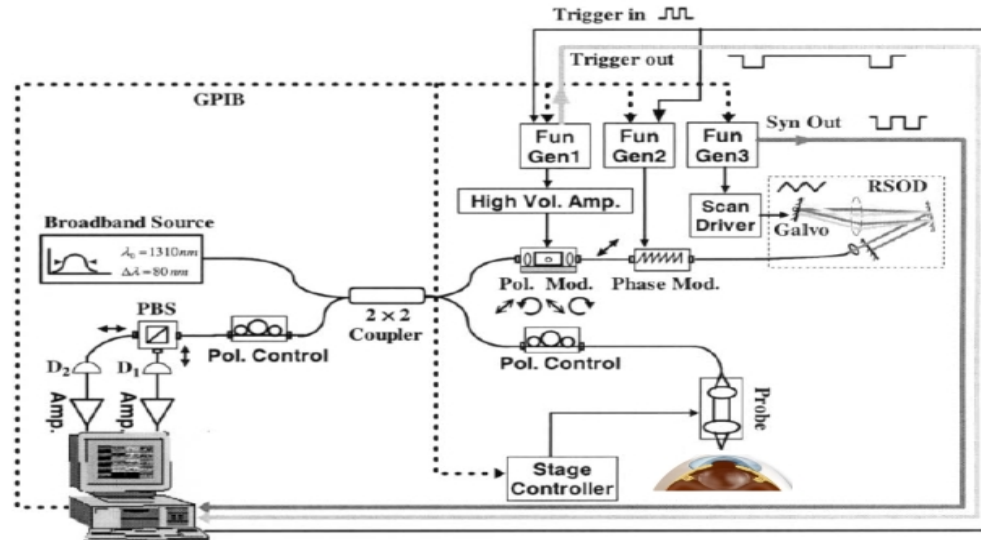


Fig. 1. Schematic f-OCT setup for imaging corneas

3. Results

We found that incision construction (specifically incision angle) is critical for the dynamic morphological changes of the incision wound during periods of IOP fluctuation. When the anterior chamber was well pressurized, we observed one stable incision angle range associated with stable apposition of the incision edges, suggesting good self-sealing ability. Outside this range, the incisions did not result in good apposition of the incision edges even under favorable IOP.

Table 1. Effects of Incision Angles

	Human Eyes											
Angle (°)	20*	25	30	32	33	35	37	40	45	55	63	90
Sealing if well pressurized	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
	Rabbit Eyes											
Angle (°)	-	24	30	33	66	75	86	90	97	110	-	-
Sealing if well pressurized	-	No	Yes	Yes	No	No	No	No	No	No	-	-

Symbol “*” indicates the use of two-planned incision.

In Table 1, “sealing” means that the incision is clinically identified as self-sealing when it is well pressurized (the IOP is above 20 mmHg) and the wound edges progressively separate only when the IOP drops lower than 10 mmHg. The incision angle was measured as the angle between the initial incision direction and the tangent line of the corneal surface at the incision entry point. Table 1 summarizes the stability of incisions with different incision angles made

on both human and rabbit cadaver eyes by evaluating the sealing capability of the incision wounds under IOP fluctuation.

3.1 Incision angle within the stable range

For single-planed incisions on human corneas within the 30°-40° range, we observed that when the intraocular pressure is larger than 20 mmHg, close apposition of the wound edges can effectively keep the wound in sealing state. On the contrary, an intraocular pressure lower than 10 mmHg will induce gapping of the wound edges. This pressure-dependence was in accordance with our previous study of a 20° two-planed clear cornea incision [11]. The two planes can be identified as two lines of l-m-n in cross-sectional image of Fig. 2. Thus, one interesting result is that a two-planed clear cornea cataract incision can effectively extend the stable range to 20°.

For single-planed incisions on rabbit corneas, we have not been able to study all the angles with a limited number of globes. We successfully constructed two “sealing” corneal incisions with angles of 30° and 33° on two rabbit globes. It is harder to make a good incision with an accurate angle on rabbit corneas than on human corneas. This is justified because of the different mechanical properties between the cornea material for rabbits and humans. The larger dynamic morphological changes observed in rabbit cases corresponded with the difference of mechanics properties of these two types of cornea material [14,15].

Two movies were recorded when the intraocular pressure fluctuation was simulated. One was for a 20° two-planed clear cornea incision (Fig. 2) and another one was for a 30° single-planed clear cornea incision (Fig. 3). The movies were originally recorded at a speed of 2.5 frames per second. Then it was speeded up to enhance visual effects as well as reduce movie file volume. Because the relationship of the infusion bottle’s height versus IOP was calibrated in a static state, the height value was not enough to accurately identify the intraocular pressure when IOP fluctuation induced dynamic morphological changes of incision wounds. When we recorded the movies, the OCT probe scanned across the center of cornea incision wound with scanning direction normal to the incision plane, then traveled back and repeated the scan. At the same time, by raising or lowering the infusion bottle, IOP fluctuation was simulated. One lateral scan with 200 lateral data points will take 0.4 seconds. In both movies, when the IOP reached 20 mmHg (estimation from static measurement), the wounds were well apposed while when IOP was lowered less than 10 mmHg (estimation from static measurement), wound gaps were progressively increased. In the static image of Fig. 2, l-m-n identifies the two-planed incision.

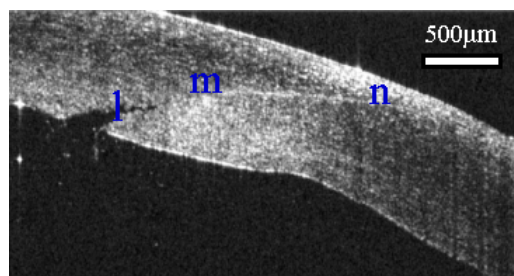


Fig. 2. (1.5 MB) Imaging a 20° two-planed clear corneal cataract incision of human eye.

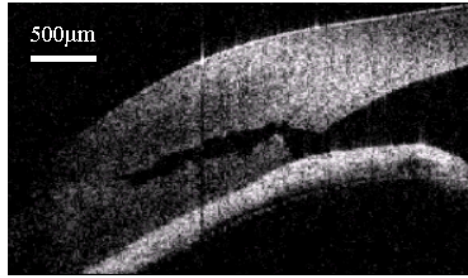


Fig. 3. (1.97 MB) Imaging a 30° rabbit clear corneal incision of rabbit eye.

3.2 Incision angle outside the stable range

For single-planned incisions on human corneas with incision angles outside the 30°-40° range, an opposite type of pressure-dependence of wound morphology was observed. Figure 4(a) shows the incision wound of 90° under IOP of 20 mmHg; Fig. 4(b) shows the incision wound of 90° under IOP of 0 mmHg. It was 20 mmHg instead of 0 mmHg that induced the wound gap. One incision wound of 55° is shown in Fig. 4(c) with 20 mmHg IOP and in Fig. 4(d) with 0 mmHg IOP. It followed the same pressure-dependent rule of an incision wound of 90°.

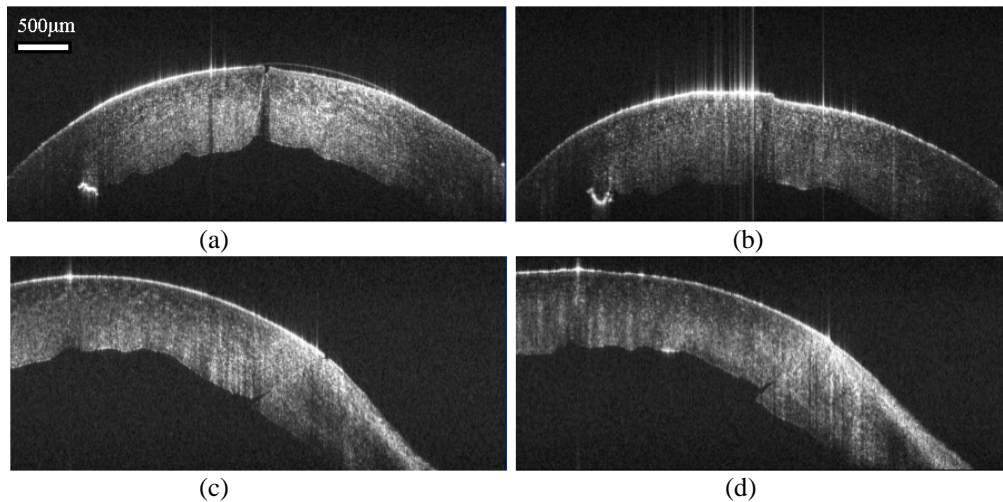


Fig. 4. Human corneal incision wounds with incision angles of (a) 90° under 20 mmHg IOP, (b) 90° under 0 mmHg IOP, (c) 55° under 20 mmHg IOP, (d) 55° under 0 mmHg IOP.

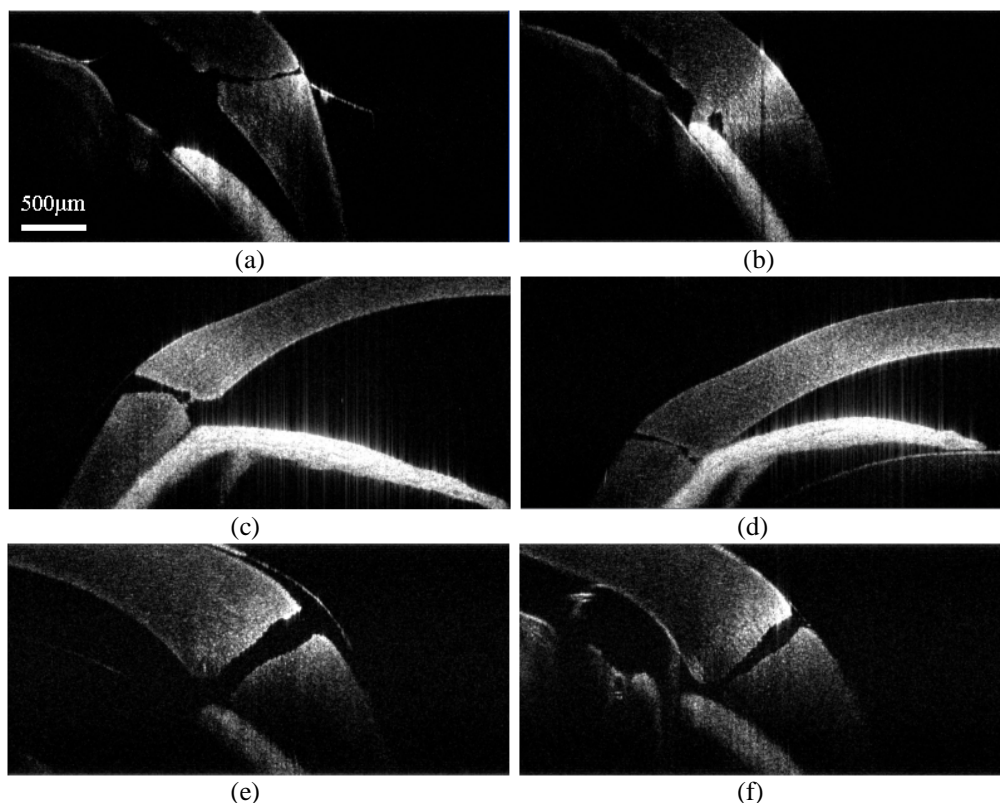


Fig. 5. Rabbit corneal incision wounds with angle of (a) 66° under 20 mmHg IOP, (b) 66° under 0 mmHg IOP, (c) 75° under 20 mmHg IOP, (d) 75° under 0 mmHg IOP, (e) 90° under 20 mmHg IOP, (f) 90° under 0 mmHg IOP.

For incisions on rabbit corneas with incision angles far away from 30° and 33° , similar pressure-dependence of wound morphology was maintained (shown in Fig. 5).

Further, one rule can be summarized from Fig. 4 and Fig. 5: the farther the incision angle is away from stable range, the larger the gap is between incision wound edges when well pressurized (20 mmHg). It is more obvious in rabbit cases than in human.

4. Discussion

Postoperative endophthalmitis is a rare but devastating complication in clear cornea cataract surgeries although proper, known antibiotic prophylaxis technologies have been adopted. In one study [16], Schmitz showed that there was a greater risk of endophthalmitis in eyes with clear corneal cataract incisions than in eyes with sclerocorneal incisions. He proposed that dehiscence and wound leakage play a major role in bacterial entry into the eye. The mechanism of bacterial entry was explored in our previous study [11]. As discussed in our previous study, such understanding will be helpful for postoperative management that is controversial in ophthalmology. In our previous study, two opposite types of pressure-dependence were observed. Here, we further explored the angle factor in construction of the corneal incision that might induce two types of pressure-dependence.

It was demonstrated that the self-sealing capability of clear corneal cataract incision is strongly dependent on the incision construction method, especially the incision angle for a single-planed construction. Although the living human eyes possess a functional endothelial pump and the mechanism of IOP is different from ex vivo human eyes, the model is still useful. The stable incision angle range for single-planed, clear corneal cataract incision of ex vivo human eyes is between 30° - 40° . Within this range, the OCT images showed more stable

incision wounds with better apposed wound edges during periods of IOP fluctuation comparable to those that might be experienced in the first hour after surgery. Incisions with angles outside this range were less capable of withstanding IOP fluctuation and always led to wound leakage. The finding of the existence of a stable incision angle range confirms the significance of incision wound construction in preventing wound leakage. We have shown that a two-planed incision can extend the stable incision angle range to 20°. There are still other factors that may affect the stability of incision wounds, such as the incision width to depth ratio and multiple-plane construction. Each of these incision construction technologies can be readily studied with optical coherence tomography technology.

The successful demonstration of OCT as an imaging modality for dynamic morphological changes of clear corneal cataract incisions suggests that OCT may be utilized to examine or test incision leakage non-invasively after completion of cataract surgery without the need for inflating the anterior chamber with balanced salt solution and applying pressure to the anterior cornea to check for wound leakage. By using OCT examination of clear corneal incisions, veteran ophthalmologists and ophthalmologists in training can acquire feedback significant to creating and maintaining self-sealing wounds. For the OCT technology itself, faster imaging speed, 3-D imaging capability as well as specialized image analyzing software integrated with an OCT instrument are desirable for in-vivo cornea imaging application.

5. Conclusion

By using non-invasive OCT technology, a stable incision angle range is found to be existent for single-planed, clear corneal cataract incisions. When well pressurized, incision angles within this relatively stable range result in well-apposed incision edges. Incision angles falling outside this range have a larger tendency for wound leakage. It is also shown that a two-planed incision can effectively expand that stable range. For incision angles outside the stable range, the farther the incision angle is away from stable range, the larger the gap between incision wound edges when well pressurized.

These findings emphasize the significance of incision construction to the self-sealing properties of clear corneal cataract incisions. Our results indicate that OCT is an efficient imaging and monitoring modality for clear corneal cataract surgery.

Acknowledgments

This work was supported by research grants awarded by the National Science Foundation (BES-86924) and National Institutes of Health (EB-00293, NCI-91717, RR-01192, EY-10335). Institute support from the Air Force Office of Scientific Research (F49620-00-1-0371), the Alcon Research Institute and the Beckman Laser Institute Endowment is also gratefully acknowledged.