Schlemm's Canal Expansion After Uncomplicated Phacoemulsification Surgery: An Optical Coherence Tomography Study

Zhennan Zhao,[1,2] Xiangjia Zhu,[1,2] Wenwen He,[1,2] Chunhui Jiang,[1–3] and Yi Lu[1,2]

[1]Department of Ophthalmology and Vision Science, Eye and ENT Hospital, Fudan University, Shanghai, People's Republic of China
[2]Key Laboratory of Myopia of State Health Ministry, and Key Laboratory of Visual Impairment and Restoration of Shanghai, Shanghai, People's Republic of China
[3]Department of Ophthalmology, No. 5 People's Hospital of Shanghai, Shanghai, China

Correspondence: Yi Lu, Department of Ophthalmology and Vision Science, Eye and ENT Hospital, Fudan University, 83 Fenyang Road, Shanghai, People's Republic of China; luyieent@126.com.
Chunhui Jiang, Department of Ophthalmology and Vision Science, Eye and ENT Hospital, Fudan University, 83 Fenyang Road, Shanghai, People's Republic of China; Chhijiang70@163.com.

ZZ and XZ contributed equally to the work presented here and should therefore be regarded as equivalent authors.

Submitted: August 22, 2016
Accepted: October 27, 2016

Citation: Zhao Z, Zhu X, He W, Jiang C, Lu Y. Schlemm's canal expansion after uncomplicated phacoemulsification surgery: an optical coherence tomography study. *Invest Ophthalmol Vis Sci*. 2016;57:6507–6512. DOI: 10.1167/iovs.16-20583

Purpose. To evaluate the effects of phacoemulsification cataract surgery on Schlemm's canal (SC) using swept-source optical coherence tomography (OCT).

Methods. Patients with a senile cataract were included. The SC area and diameter were checked by OCT at the baseline and 1 day, 1 week, 1 month, and 6 months after the cataract surgery. Multivariate linear regression analysis was performed for predictors of change in the mean SC area and diameter.

Results. Twenty-five eyes (25 patients) were included in the final analysis. After the cataract surgery, there was a significant increase in the SC area and diameter, and a decrease in the intraocular pressure (IOP) (repeated-measures analysis of variance; all $P < 0.05$), which extended to the end of the follow-up period. After multivariate analysis, the changes in the SC area and diameter 6 months after surgery were correlated with the change in the IOP (SC area, $\beta = -0.575$, $P < 0.0001$; SC diameter, $\beta = -0.576$, $P < 0.0001$) and the change in the anterior vault (AV) (SC area, $\beta = 0.359$, $P = 0.007$; SC diameter, $\beta = 0.413$, $P = 0.003$).

Conclusions. Expansion of the SC was observed after cataract surgery. The degree of expansion was related to the extent of the decrease in the IOP. Further studies are needed to determine whether these changes will last over a long period of time.

Keywords: Schlemm's canal, phacoemulsification, swept-source optical coherence tomography

Phacoemulsification with intraocular lens (IOL) implantation is one of the most common ophthalmic surgical procedures, and a decrease in intraocular pressure (IOP) after this surgery has been well documented in patients with and without glaucoma.[1–8] The mechanisms behind this are still a pending issue. As a mean resistance point of the aqueous pathway in the eye, the Schlemm's canal (SC) alone may explain approximately 50% of the decrease in aqueous outflow facility.[9] Its size is related to outflow facility and may be related to the IOP.[10] Previous studies suggested that the tension placed on the scleral spur (SS) and the trabecular meshwork (TM) during lens depression induced substantial increases in aqueous outflow facility.[11,12] After cataract surgery, the anterior segment may experience changes similar to lens depression.[13] Whether these changes could change the SC's size and cause a reduction in IOP is still unknown.

With the emergence of the swept-source technique in recent years, the imaging resolution and acquisition speed of optical coherence tomography (OCT) have been revolutionized. This has led to more detailed anterior chamber angle (ACA) architecture observation and has improved our understanding of structural changes in the SC in vivo.[14–16]

In this study, using swept-source OCT, we have attempted to evaluate the effects of phacoemulsification cataract surgery on the SC, IOP, and anterior chamber parameters, as well as the ACA after surgery in subjects with cataracts.

Materials and Methods

Participants were enrolled from the Eye and ENT Hospital, Fudan University, Shanghai, China, from May to July 2015. The subjects enrolled in this study had visually significant cataracts but no other eye diseases, and had been admitted for phacoemulsification surgery with IOL implantation. If both of the subject's eyes qualified for the study, only the first operation eye was enrolled. This research was approved by the Institutional Review Board and followed the tenets of the Declaration of Helsinki. All subjects signed informed consent forms.

Exclusion criteria included eyes with glaucoma (glaucomatous visual loss or optic neuropathy determined by optic disc cupping); a preoperative IOP > 21 mm Hg; a narrow or closed AC angle (Shaffer classification with a grade of 0 or 1, at least two quadrants); and pseudoexfoliation syndrome. Also excluded

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were those with a history of ocular trauma or intraocular surgery; corneal abnormalities, including scarring, dystrophy, and corneal opacity; uveitis; severe retinal diseases; and intraoperative or postoperative complications caused by cataract surgery. The use of topical or systemic medications that might influence the IOP measurements was also grounds for exclusion.

All the subjects who were enrolled in this study underwent complete ophthalmologic examinations, including best-corrected visual acuity (BCVA) in logMAR, slit-lamp biomicroscopy, and cataract grading lens opacities classification III (LOCS III). The subjects also had refraction measurements using an autorefractor (NIDEK ARK-700A, Aichi, Japan), which was further refined by an experienced optometrist, followed by a calculation of the spherical equivalent (SE) using the spherical diopter (D) plus one-half of the cylindrical dioptric power. The corneal K value was also obtained using the same autorefractor. Furthermore, subjects received a dilated fundus examination using a three-mirror contact lens; IOP was measured using Goldmann applanation tonometry by a single trained ophthalmologist (WH); and axial length (AL) measurement was performed using an IOLmaster (Carl Ziess, Inc., Jena, Germany). Gonioscopy was performed using a gonioscope (Volk G-1 trabeculum; Volk Optical, Inc., Mentor, OH, USA), and the angle was given Shaffer grades by an ophthalmologist (XZ). Each patient's medical and family histories were also collected. Measurements of the OCT, AL, IOP, K value, and BCVA were obtained before the phacoemulsification surgery. The OCT, BCVA, K value, and IOP measurements were also obtained 1 day, 1 week, 1 month, and 6 months after surgery.

OCT Data Acquisition and Processing

The swept-source OCT (CASIA SS-1000; Tomey Corporation, Nagoya, Japan) is specifically designed for anterior segment imaging using a 1310-nm wavelength with a scan speed of 30,000 A-scans/second and an axial resolution of less than 10 μm. The eyes were imaged with two protocols under dark room conditions by the same examiner (ZZ). These were a three-dimensional-angle high-definition scan (HD, a raster of 64 B-scans each with 512 A-scans over 8 mm) and a low-density scan (LD, 128 radial scans each with 512 A-scans over 16 mm). The scans were performed independently in nasal and temporal quadrants (3 and 9 o'clock positions). The superior and inferior quadrants were not observed in the current study because these portions were often covered with the upper or lower eyelids, and in order to expose these quadrants, pulling the eyelids during these scan acquisitions would be necessary. With the LD protocol, images of the temporal and nasal angles were obtained simultaneously in one horizontal image centered on the corneal center. With the HD protocol, the temporal and nasal limbus were imaged separately after adjusting the fixture to the nasal and temporal areas. During the examination, the subjects were encouraged to open their eyes as wide as possible. If necessary, the examiner gently helped them to keep their eyes open by using his fingers, taking care to avoid pressing on the eye. To avoid the effects of dynamic variations, all measurements were obtained from 9:00 to 12:00 AM.

The scans of each site were repeated multiple times (at least three times), and three images were chosen for final analysis based on image quality. For each image, the length of the SC and the TM, and as after the cataract surgery, the area of the SC were assessed and then quantified manually by two masked operators (XZ and WH) using the software built in to the apparatus with the HD mode. The SC length was defined as the meridional AL of the thin, black, lucent space on the HD images (Fig. 1). The SC area was drawn freehand and depicted the area surrounded by the outline of the SC (Fig. 1). The SS was defined as the point between the TM and the ciliary body. The TM length was defined as the meridional AL between the SS and the anterior endpoint of the TM. The mean of the nasal and temporal SC and TM measurements from each OCT image was used in the analysis.

The angle opening distance (AOD), trabecular iris space area (TISA), and trabecular–iris angle (TIA), as well as the anterior vault (AV) after the cataract surgery, were automatically analyzed after the SS was manually located using the LD scan protocol. AOD500 was defined as the perpendicular distance between the TM and the iris at 500 μm anterior to the SS. TISA500 was a trapezoidal area, bounded anteriorly by the AOD500 and posteriorly by a line drawn from the SS perpendicular to the plane of the inner scleral wall to the opposing iris, superiorly by the inner corneoscleral wall, and inferiorly by the iris surface. TIA500 was defined as an angle measured between the apex of the iris recess and the arms of the angle passing through a point on the TM 500 μm from the SS and the point on the iris perpendicularly. The AV was defined as the maximum perpendicular distance between the posterior corneal surface and a horizontal line connecting the two SS. The anterior chamber depth (ACD) was defined as the perpendicular distance between the corneal endothelium at the corneal apex to the anterior lens surface. The central corneal thickness (CCT) was defined as the vertical distance between the inner border of the endothelia and the upper outer border of the epithelia at the corneal center.

Surgical Technique

Cataract surgeries were performed by one experienced surgeon (YL) using the INFINITI Vision System (Alcon Laboratories, Inc., Fort Worth, TX, USA). Briefly, after topical anesthesia was administered, a 2.2-mm clear corneal self-sealing incision, continuous capsulorhexis, hydrodisection, phacoemulsification, and irrigation/aspiration of the residual lens cortex were sequentially performed. A one-piece foldable IOL (AcrySof IQ SN60WF or SN6AD1; Alcon Laboratories, Inc.) was then implanted in the capsular bag. The total phacoemulsification time and the phacoemulsification energy (%) of the phacoemulsification machine were documented.

Postoperative treatment consisted of 1% prednisolone acetate (Allergan Pharmaceuticals Ireland, Westport, Ireland) and 0.5% levofloxacin (Santen Pharmaceutical Co., Ltd., Osaka, Japan) eye drops four times a day for 2 weeks, and 0.1% diclofenac sodium (Shenyang Sinqi Pharmaceutical Co., Ltd., Shenyang, China) eye drops four times a day for 1 month.

Statistical Analysis

Statistical analysis was performed using SPSS for Mac (Version 23.0; SPSS, Inc., Chicago, IL, USA). The preoperative and postoperative measurements were analyzed using the mixed-effects model, and post hoc analyses used the Bonferroni test. Kolmogorov-Smirnov test was used to check whether the measurements were normally distributed or not, and all of these parameters were normally distributed. Student's t-test was used to analyze the differences between males and females and between right and left eyes. Spearman or Pearson correlation was used to compare the data between the parameters. Multivariate linear regression analysis with stepwise methods was then performed to identify predictors for changes in the mean SC diameter or area. This was performed from baseline to 6 months after surgery (hereafter denoted as ΔSCD or ΔSCA), using parameters that showed significance at less than the 0.1 level in univariate analysis, and excluding those that showed multicollinearity. Only P values less than 0.05 were considered statistically significant.

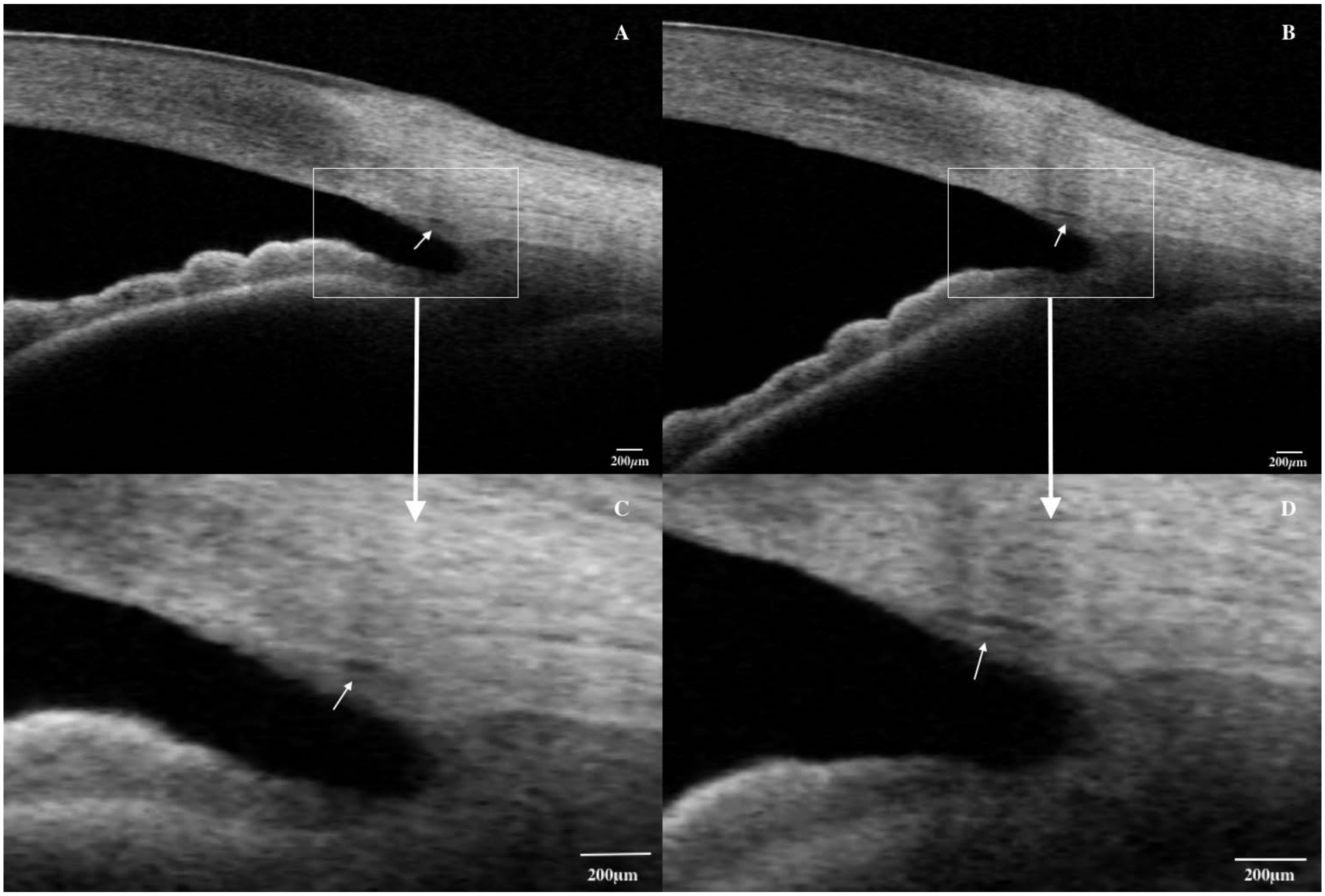

FIGURE 1. The SC (*white arrow*) morphology changes after cataract surgery in a 65-year-old female subject. (**A**, **B**) Baseline and 6 months postoperatively, respectively. (**C**, **D**) High-magnification images of the *white boxes* in (**A**, **B**), respectively. The SC area and diameter were 3263 μm^2 and 128 μm for (**A**) and 13582 μm^2 and 275 μm for (**B**), respectively.

RESULTS

Twenty-seven eyes of 27 patients with a senile cataract fulfilled the assessment visits at baseline and after surgery. Two were excluded from further analysis due to the difficulty in identifying the SC in the OCT images. As a result, 25 eyes (10 males, 15 females) were included in the final analysis (92.59%), 11 of which were right eyes. The subjects' mean age was 64.88 ± 10.61 years; the mean AL was 24.60 ± 2.48 mm; the mean nuclear opalescence (NO) was 3.18 ± 0.61; the mean cortical opacity was 2.72 ± 0.74; the mean BCVA was 0.96 ± 0.51; the total phacoemulsification time was 47.54 ± 20.99 seconds, and the mean phacoemulsification energy was 34.89 ± 16.01%. Differences in parameter measurements were not statistically significant between right and left eyes or between males and females (all $P > 0.05$).

After the cataract surgery, the ACD, TM length, and AV was significantly increased (all $P < 0.001$) (Table 1), while the K value remained unchanged during all visits. The CCT was at an increased level 1 day after surgery, but returned to the baseline thereafter. The IOP was significantly lower during all postoperative examinations ($P < 0.001$) (Table 1). At 6 months after surgery, the mean decrease of IOP was 2.66 ± 1.87 mm Hg.

An increase in SC measurement was found. One day after surgery, the SC diameter and area increased significantly, and this increase was maintained to the end of the follow-up period (all $P < 0.05$, Table 1; 95% confidence interval [CI]) for Δarea, 1488.33–3112.26 μm^2, 1094.79–6886.17 μm^2, 2723.43–4937.69 μm^2, and 3185.65–5837.35 μm^2 for 1 day, 1 week, 1 month, and 6 months, respectively; 95% CI for Δdiameter, 24.08–91.06 μm, 38.56–116.40 μm, 54.41–132.85 μm, and 75.54–154.72 μm for 1 day, 1 week, 1 month, and 6 months, respectively). Furthermore, compared to the measurements made 1 day after surgery, the SC diameter and area were greater 1 month and 6 months after surgery ($P < 0.001$, Table 1). There was also a significant change in the postoperative ACA parameters. The AOD500, TISA500, and TIA500 increased significantly at 1 day, 1 week, 1 month, and 6 months after the cataract surgery (all $P < 0.0001$, Table 1).

By analyzing the changes of the SC and other parameters taken from each eye from baseline to 6 months after surgery, we observed that the changes in the SC area and diameter were correlated to the change in the IOP (SC area, $\beta = -0.575$, $P < 0.0001$, Fig. 2A; SC diameter, $\beta = -0.576$, $P < 0.0001$, Fig. 2B) and the change in AV (SC area, $\beta = 0.359$, $P = 0.007$; SC diameter, $\beta = 0.413$, $P = 0.003$). The linear regression analysis found no association between changes in SC and other factors such as age, sex, AL, CCT, phacoemulsification time/energy, baseline ACD and the change in ACD, baseline IOP, baseline TM and the change in TM length, or baseline ACA measurements and the change in ACA measurements (Table 2).

DISCUSSION

This study investigated changes in the SC after cataract surgery. A significant increase in the SC diameter and area and a decrease in the IOP were found after cataract surgery. An increase in the TM length and the AV was also recorded. These changes remained for at least 6 months after surgery. In

Table 1. The BCVA in LogMAR, CCT, Corneal K Value, Anterior Chamber Parameters, IOP, SC Morphology, and ACA Parameters at Different Time Points

Parameters	Baseline, n = 25	1D, n = 25	1W, n = 25	1M, n = 25	6M, n = 25	P Values	Pohc
BCVA, logMAR	0.96 ± 0.52	0.36 ± 0.44	0.24 ± 0.47	0.21 ± 0.46	0.20 ± 0.45	<0.0001	Baseline > 1D > 1W/1M/6M
CCT, μm	533.76 ± 36.90	601.56 ± 58.26	547.00 ± 38.71	538.52 ± 37.75	536.10 ± 36.75	<0.0001	1D > Baseline/1W/1M/6M
K value	43.93 ± 1.711	44.01 ± 1.657	44.00 ± 1.744	44.09 ± 1.672	44.03 ± 1.684	0.2087	-
AV, mm	3.045 ± 0.2003	3.079 ± 0.2198	3.128 ± 0.2253	3.128 ± 0.2251	3.141 ± 0.1906	<0.0001	6M/1M/1W > 1D > Baseline
ACD, mm	2.75 ± 0.41	3.71 ± 0.48	3.85 ± 0.42	3.90 ± 0.50	3.88 ± 0.41	<0.0001	6M/1M/1W/1D > Baseline
IOP, mm Hg	13.95 ± 4.16	12.01 ± 2.67	10.27 ± 4.47	11.27 ± 3.00	11.29 ± 3.89	<0.0001	Baseline > 1D/1W/1M/6M
SC diameter, μm	243.30 ± 42.73	300.91 ± 51.08	320.81 ± 58.96	336.92 ± 57.12	358.40 ± 63.32	<0.0001	(6M/1M > 1D)/1W > Baseline
SC area, $μm^2$	4030.11 ± 913.82	6335.22 ± 1419.07	8021.36 ± 1485.52	7869.85 ± 1491.19	8541.11 ± 2044.23	<0.0001	(6M/1M > 1D)/1W > Baseline
TM length, μm	681.93 ± 70.76	727.59 ± 76.31	737.18 ± 78.24	753.82 ± 76.60	752.45 ± 71.61	<0.0001	6M/1M/1W/1D > Baseline
AOD500, mm	0.47 ± 0.24	0.70 ± 0.17	0.69 ± 0.18	0.68 ± 0.16	0.67 ± 0.15	<0.0001	6M/1M/1W/1D > Baseline
TISA500, mm^2	0.18 ± 0.09	0.26 ± 0.07	0.25 ± 0.07	0.28 ± 0.08	0.26 ± 0.07	<0.0001	6M/1M/1W/1D > Baseline
TIA500,°	33.75 ± 12.24	46.84 ± 9.47	44.76 ± 6.03	46.10 ± 7.35	46.87 ± 7.75	<0.0001	6M/1M/1W/1D > Baseline

Data are presented as the mean ± SD. 1D, 1 day; 1W, 1 week; 1M, 1 month; 6M, 6 months postoperatively; Pohc, post hoc analysis.

addition, multivariate linear regression showed that changes in the SC were negatively correlated with changes in the IOP, and positively correlated with changes in the AV 6 months after surgery.

Measurements of human SC dimensions have, until recently, been limited to the histologic sections. With the development of the OCT technique, the structures of the aqueous outflow pathway, such as the SC and the TM, can be noninvasively evaluated in human eyes, with excellent repeatability and reliability.[15,17] Using the same OCT apparatus, Usui et al.[15] revealed that the SC was observable with the HD mode, with a high detection rate (approximately 90%) in living human subjects. This is similar to the rate observed in our results (92.59%). The average SC diameter value among normal subjects was given by Shi et al.[18] as 266.96 ± 49.55 μm. Our results at baseline were 243.3 ± 42.73 μm and are close to those observed by Shi et al.[18] Furthermore, the mean SC area measurement in the present study was 4030.11 ± 913.82 $μm^2$, which is also compatible with the results of Kagemann et al. (4064 ± 1308 $μm^2$).[19] These comparisons demonstrate the reliability of our results.

To date, this is the first observation using OCT that shows expansion of the SC and the TM after cataract surgery in vivo. Van Buskirk and Grant[11,12] induced substantial increases in the aqueous outflow facility through lens depression, which was correlated with a widening TM and an increased diameter of the SC histologically.[11,12] The mechanism by which posterior lens displacement facilitates aqueous outflow presumably involves alterations in zonular tension vectors transmitted to the SS, ciliary body, and the TM.[20] Lens exchange with phacoemulsification and IOL implantation appears to return the age-related anterior displacement structures (including the ciliary body and iris root) to the position they were in earlier in life, as described by Strenk et al.[13] using magnetic resonance imaging (MRI) in vivo. As the distance between the posterior corneal surface and the horizontal line connecting the two SS on the OCT scans, the AV increased after cataract surgery in the current study; meanwhile, the corneal K value remained unchanged. These changes also indicate the posterior displacement of the SS after cataract surgery. This lens depression-like alteration after cataract surgery might increase posterior traction on the SS, expanding the TM and the lumen of the SC, as observed in the current study. Furthermore, the positive relationship between changes in the AV and the SC after surgery, as seen in the current study, provide further evidence for the hypothesis mentioned above.

Another possible reason for the change in SC morphology could be the ciliary muscle contractility following cataract surgery. Magnetic resonance imaging has revealed an age-related decrease in the ciliary ring diameter in humans, which is reversed after cataract surgery.[13,21] Park et al.[22] revealed that the centripetal movement of the human ciliary body and ciliary muscle contractility increased significantly after cataract surgery. Furthermore, Mehdizaden[23] pointed out that increases in the ciliary ring, like increases in the preload in the heart, might lead to more contractility of the ciliary muscles. Thus, ciliary muscle contraction might exert tension on the SS and enlarge the SC after cataract surgery.

It was found that after cataract surgery the area of the anterior capsule opening constricted rapidly during the first month and more slowly thereafter.[24,25] Cekic and Batman[26] reported that a 4.0-mm capsulorhexis places more traction on the zonulas and results in a lower IOP than a 6.0-mm capsulorhexis 1 month after surgery. These studies indicate that postoperative capsule fibrosis and capsule contraction may also contribute to the SC expansion, and may explain the

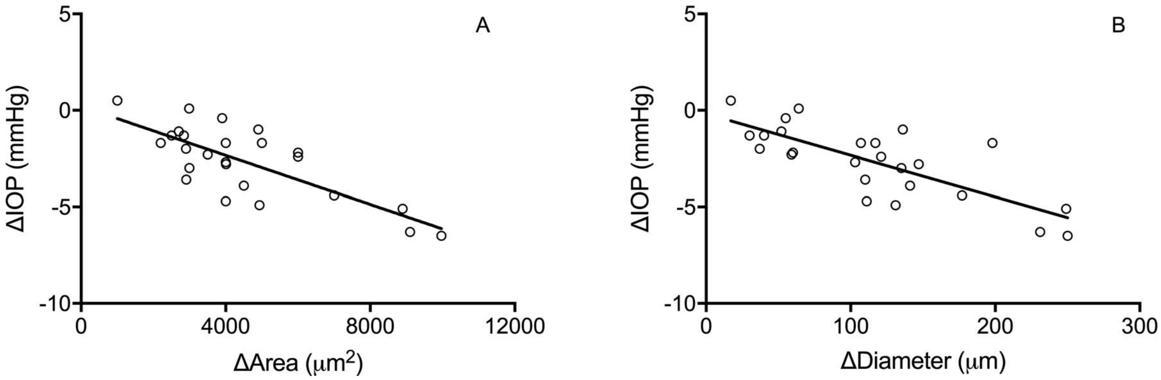

Figure 2. Scatter plot of ΔIOP versus ΔSC area (**A**)/diameter (**B**) 6 months after cataract surgery.

gradual expansion of the SC within 1 month of surgery in our study.

The effect of cataract surgery on the IOP has been investigated by many researchers, and our results support the significant IOP reduction after cataract surgery.[1–8] Although several hypotheses have been proposed to explain this effect, there have been no confirmed explanations to date. In this study, to elucidate the mechanism underlying IOP change, swept-source OCT was employed, and the relationship between IOP change and SC changes 6 months after cataract surgery was revealed. Through the use of OCT imaging, the increase in the outflow facility in living mice appears to be caused by an expansion of the SC lumen.[27] Hong et al.[28] reported that an enlarged SC might be an additional mechanism for the decreased IOP seen in trabeculectomy in primary angle-closure glaucoma. Our results suggested that the expansion of the SC after cataract surgery might also improve the valves in the SC, increase the facility of outflow, and decrease IOP in healthy subjects.

The ACD deepen and the ACA widen following cataract surgery, and their relationship to IOP reduction has been reported in several studies.[4,6,29–32] Similar morphologic changes were found in our study, although none of these alterations correlated with changes in the SC. This indicates that the effect of these structural changes on the IOP might not be achieved by the SC.

One limitation of this study is that whether and when the increase in the SC area and diameter will return to baseline levels, such as 12 months or more after surgery, is still unclear. As the implanted artificial lens does not enlarge over time and the IOP reductions are sustained over 10 years,[7] it seems likely that the SC expansion may be sustained over a long period. Therefore, further investigations with a longer follow-up period should be considered.

Table 2. Univariate and Multivariate Linear Regression Analysis for Predictors of Changes in the SC 6 Months After Cataract Surgery

	ΔSCA				ΔSCD			
	Univariate		Multivariate		Univariate		Multivariate	
Parameters	*β*	*P* Values	*β*	*P* Values	*β*	*P* Values	*β*	*P* Values
Age	−0.275	0.192	–	–	−0.205	0.163	–	–
Sex	−0.256	0.108	–	–	−0.188	0.185	–	–
AL	0.177	0.198	–	–	−0.388	0.442	–	–
C	−0.162	0.220	–	–	−0.267	0.199	–	–
N	−0.042	0.421	–	–	0.063	0.382	–	–
CCT	−0.243	0.121	–	–	−0.101	0.316	–	–
Phaco energy	−0.112	0.297	–	–	−0.202	0.166	–	–
Phaco time	−0.037	0.430	–	–	−0.019	0.464	–	–
Baseline IOP	0.403	0.023	0.115	0.369	0.346	0.045	0.044	0.719
Baseline ACD	−0.075	0.360	–	–	−0.317	0.061	0.012	0.921
Baseline AV	−0.301	0.072	0.018	0.890	−0.484	0.187	–	–
Baseline TM length	0.429	0.016	0.218	0.076	0.423	0.217	–	–
Baseline AOD500	0.101	0.315	–	–	−0.062	0.384	–	–
Baseline TISA500	0.149	0.239	–	–	−0.017	0.469	–	–
Baseline TIA500	0.027	0.449	–	–	−0.116	0.291	–	–
ΔIOP	−0.763	<0.0001	−0.575	<0.0001	−0.773	<0.0001	−0.576	<0.0001
ΔACD	−0.194	0.177	–	–	−0.239	0.125	–	–
ΔAV	0.669	0.0005	0.395	0.007	0.688	0.0001	0.413	0.003
ΔTM length	−0.439	0.114	–	–	−0.505	0.051	−0.174	0.172
ΔAOD500	−0.186	0.187	–	–	−0.152	0.235	–	–
ΔTISA500	−0.204	0.164	–	–	−0.283	0.186	–	–
ΔTIA500	−0.096	0.323	–	–	−0.055	0.398	–	–

ΔSCA, changes in the mean Schlemm's canal area at 6 months postoperatively; ΔSCD, changes in the mean Schlemm's canal diameter at 6 months postoperatively; C, cortical opacity; N, nuclear opalescence.

After cataract surgery, the SC morphologic measurements increased significantly, and this increase was accompanied by a decrease in IOP. Whether such changes might affect the IOP in the long term still needs to be verified.

Acknowledgments

Supported by research grants from the National Natural Science Foundation of China (Grant 81270989) and the Scientific Research Program, Science and Technology Commission of Shanghai Municipality, Shanghai (Grant 14430721100).

Disclosure: **Z. Zhao**, None; **X. Zhu**, None; **W. He**, None; **C. Jiang**, None; **Y. Lu**, None

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