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

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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, β = −0.575, P < 0.0001; SC diameter, β = −0.576, P < 0.0001) and the change in the anterior vault (AV) (SC area, β = 0.359, P = 0.007; SC diameter, β = 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 pseudoxefosilation syndrome. Also excluded...
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 dioptric (D) plus one-half of the cylindrical dioptic 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 Zeiss, 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 (CASIAR 5100; 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 quadrants (3 and 9 o’clock positions). The superior and inferior quadrants were sequentially performed. A one-piece foldable IOL (AcrySof IQ SN60WF or SN6AD1; Alcon Laboratories, Inc., Fort Worth, TX, USA) was then implanted in the capsular bag. The total phacoemulsification time and the phacoemulsification energy (%) of the phacoemulsification machine were documented.

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.
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 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, 1488.35–3112.26 µm², 1094.79–6886.17 µm², 2723.43–4937.69 µm², and 5185.65–5837.35 µm² 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, β = −0.575, P < 0.0001, Fig. 2A; SC diameter, β = 0.576, P < 0.0001, Fig. 2B) and the change in AV (SC area, β = 0.359; P = 0.007; SC diameter, β = 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 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
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.\textsuperscript{15, 17} Using the same OCT apparatus, Usui et al.\textsuperscript{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.\textsuperscript{18} as 266.96 ± 49.53 μm. Our results at baseline were 243.3 ± 42.73 μm and are close to those observed by Shi et al.\textsuperscript{18} Furthermore, the mean SC area measurement in the present study was 4050.11 ± 913.82 μm\textsuperscript{2}, which is also compatible with the results of Kagemann et al.\textsuperscript{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\textsuperscript{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.\textsuperscript{11, 12} The mechanism by which 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.\textsuperscript{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.\textsuperscript{13, 21} Park et al.\textsuperscript{22} revealed that the centripetal movement of the human ciliary body and ciliary muscle contractility increased significantly after cataract surgery. Furthermore, Mehdizaden\textsuperscript{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 contracture 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.\textsuperscript{23, 25} Cekic and Bateman\textsuperscript{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 contracture may also contribute to the SC expansion, and may explain the...
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.

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ΔSCA Univariate</th>
<th>ΔSCA Multivariate</th>
<th>ΔSCD Univariate</th>
<th>ΔSCD Multivariate</th>
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<tr>
<td>Age</td>
<td>β</td>
<td>P Values</td>
<td>β</td>
<td>P Values</td>
</tr>
<tr>
<td>Sex</td>
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<td>0.192</td>
<td>−</td>
<td>−</td>
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<td>AL</td>
<td>−0.256</td>
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<td>0.177</td>
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<td>C</td>
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<td>−</td>
<td>−</td>
</tr>
<tr>
<td>N</td>
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<td>0.421</td>
<td>−</td>
<td>−</td>
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<td>CCT</td>
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<td>−</td>
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<td>Phaco energy</td>
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<tr>
<td>Phaco time</td>
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<td>Baseline IOP</td>
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<td>Baseline ACD</td>
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<td>−</td>
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<tr>
<td>Baseline AV</td>
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<td>0.072</td>
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<td>Baseline TM length</td>
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<td>0.016</td>
<td>0.218</td>
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<td>Baseline AOD500</td>
<td>0.101</td>
<td>0.315</td>
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<td>−</td>
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<tr>
<td>Baseline TISA500</td>
<td>0.149</td>
<td>0.239</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Baseline TIA500</td>
<td>0.027</td>
<td>0.449</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>ΔIOP</td>
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<td>&lt;0.0001</td>
<td>−0.575</td>
<td>&lt;0.0001</td>
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<tr>
<td>ΔACD</td>
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<td>0.177</td>
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<td>−</td>
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<tr>
<td>ΔAV</td>
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<td>0.0005</td>
<td>0.395</td>
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<tr>
<td>ΔTM length</td>
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<td>ΔAOD500</td>
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<td>0.187</td>
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<tr>
<td>ΔTISA500</td>
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<td>0.164</td>
<td>−</td>
<td>−</td>
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<tr>
<td>ΔTIA500</td>
<td>−0.096</td>
<td>0.323</td>
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</tbody>
</table>

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.

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References