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ORIGINAL PAPER

Observation of anterior chamber volume after cataract surgery with swept-source optical coherence tomography

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Abstract
Purpose To investigate the changes in the anterior chamber volume (ACV) with swept-source optical coherence tomography (SS-OCT) after cataract surgery and the factors that influence these ACV changes.
Methods This was a prospective cohort study. Fifty-one patients who underwent cataract surgery were enrolled. Their ACV, anterior chamber depth, and angle widths were measured with SS-OCT before and 1 day, 1 week, and 1 month after surgery. The associations between the changes in ACV and posterior vitreous detachment (PVD) and axial length (AXL) were determined.
Results Compared with the preoperative volume, ACV increased significantly at all three time points after surgery (all $p < 0.001$). ACV was greater at 1 week after surgery than at 1 day after surgery ($p < 0.001$). Both AXL and the presence of PVD were significantly associated with the change in ACV at 1 day after surgery ($p = 0.005$). However, neither PVD nor AXL affected the change in ACV between 1 day and 1 week after surgery.
Conclusions ACV stabilized in the first week after cataract surgery. The absorption of irrigation fluid and balanced salt solution in the vitreous cavity contributed to the change in ACV 1 week after surgery. Eyes with longer AXL and PVD tended to show less change in ACV at 1 day after surgery.

Keywords Anterior chamber volume · Cataract surgery · Optical coherence tomography · Posterior vitreous detachment · Axial length · Phacoemulsification

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Introduction

Fluctuations in refractive status in the early period after cataract surgery are likely to affect the patient's uncorrected visual acuity (UCVA), and consequently his/her satisfaction with cataract surgery. The corneal thickness, refraction, and fundus changes are usually assessed at this time [1, 2]. The position of the intraocular lens (IOL) is associated with postoperative refraction because it alters the final focus of the lOL. The anterior chamber volume (ACV) is closely associated with the position of the IOL, but this factor has not been adequately evaluated because there has been no instruments to measure ACV.

With the recent introduction of swept-source optical coherence tomography (SS-OCT), which was specifically designed to image the anterior segment with a substantially improved scan speed (30,000 A-scans per second), we can now accurately measure the anterior chamber parameters in < 1 s. Therefore, we can now measure ACV. Intraoperative irrigation is used to prevent anterior chamber collapse during phacoemulsification, and balanced salt solution (BSS) is also injected into the eye to hydrate the incision during cataract surgery. The ACV measured immediately after the hydrated incision is likely to be affected not only by the removal of the opaque lens, but also the amount of fluid entering the eyeball during the procedure. Unfortunately, few studies have examined this phenomenon.

In the present study, we used SS-OCT to measure the changes in ACV over time after cataract surgery, and evaluated the factors potentially influencing these changes.

Methods

Subjects and collection

This study was registered at www.clinicaltrials.gov (clinical trial accession number: NCT02182921) and was approved by the Institutional Review Board of the Eye & ENT Hospital of Fudan University. All procedures were performed in accordance with the Declaration of Helsinki and with the approved research protocol. Informed consent was obtained from all the participants before their enrolment.

Fifty-one eyes of 51 patients that underwent uneventful phacoemulsification and posterior chamber IOL implantation at the Eye and ENT Hospital of Fudan University between May 2015 and July 2015 were consecutively enrolled in this study. Eyes with significant zonular weakness, corneal disease, fundus pathology, previous trauma, glaucoma, or diabetic retinopathy were excluded from the study.

Preoperative examinations

Routine ophthalmic examinations were conducted before surgery. The axial length (AXL) was measured with an IOLMaster (Carl Zeiss AG, Oberkochen, Germany). Posterior vitreous detachment (PVD) was evaluated by one experienced technician using B-scans. Biometry measurements of the anterior segment, including ACV, anterior chamber depth (ACD), and angle widths, were made with SS-OCT (CASIA SS-1000 OCT; Tomey Corporation, Nagoya, Japan), as previously described [3]. The total scan time was less than 0.3 s when the patients co-operated well by focusing on the internal target and if the entire cornea was exposed. All examinations were conducted without pupil dilation in a room under illumination of 336 lx. In total, 128 radial slices (each 6 mm in depth and 16 mm in length) were acquired, and 64 B-scans were analyzed to measure the ACV of each eye. During the examination, ACV was automatically calculated from eight slices using the volume protocol: 0°–180°, 23°–203°, 45°–225°, 68°–248°, 90°–270°, 113°–293°, 135°–315°, and 158°–338°. The instrument software automatically detects the boundaries of the cornea, iris, and lens on each image, and manual adjustment was only required if the software was unable to automatically detect these boundaries. ACV was automatically calculated by the system's software. Images with eyelid or motion effects were excluded. ACD was measured after manual identification of the angle recess. The angle width parameters derived with SS-OCT included the angle opening distance 500 (AOD500), the trabecular iris space area 500 (TISA500), the angle recess area 500 (ARA500), and the trabecular iris angle 500 (TIA500), which were determined for the superior, inferior, nasal, and temporal angles, as previously described [3].

Surgical procedures

All the procedures were performed under topical anesthesia by one experienced surgeon (Prof. Yi Lu). A 5–5.5 mm continuous curvilinear capsulorhexis was performed after a 2.6 mm clear corneal incision was made. Hydrodissection, chopping, nuclear rotation, and phacoemulsification were then performed.

Irrigation and aspiration of the cortex was followed by the implantation of the IOL into the capsular bag. We used the same IOL throughout this study, which was a Rayner 920H A. Finally, the incisions were hydrated with BBS after the viscoelastic (DisCo-Visc®; Alcon Laboratories, Inc., Fort Worth, TX, USA) was removed. Prednisolone acetate eye drops (Allergan Pharmaceuticals Ireland, Westport, County Mayo, Ireland) and levofloxacin eye drops (Cravit®; Santen Pharmaceutical Co., Ltd, Osaka, Japan) were administered four times/day for 2 weeks, and pranoprofen eye drops (Pranopulin®; Senju Pharmaceutical Co., Ltd, Osaka, Japan) were administered four times/day for 1 month after surgery.

Statistical analysis

All statistical analyses were performed with the SPSS software (version 11.0; SPSS Inc., Chicago, IL, USA). All values are presented as means ± standard deviations. Differences in quantitative variables were analyzed with Student's t test for unpaired samples, and categorical variables were compared with the χ^2 test. Repeated-measures analysis of variance (ANOVA) was used to analyze the differences in variables measured at multiple time points, with Fisher's least significant difference (LSD) post hoc test, for pairwise comparisons. Pearson's correlation coefficients were calculated to determine the correlations between quantitative variables. A multiple linear regression analysis was performed to determine the independent predictors of the change in ACV after surgery. For all tests, $p < 0.05$ was considered statistically significant.

Results

The baseline characteristics of the patients are summarized in Table 1. Overall, 33/51 (64.71%) patients suffered preoperative PVD.

Changes in anterior segment variables after surgery

Figure 1 shows the changes in ACV over time. The mean ACV was 146.1 ± 40.1 mm^3 (95% CI 128.9, 163.2) before surgery, 184.4 ± 29.4 mm^3 (95% CI 175.5, 192.6) 1 day after surgery (Fig. 2), 188.7 ± 30.3 mm^3 (95% CI 180.4, 195.0) 1 week after surgery, and 188.3 ± 25.6 mm^3 (95% CI 177.6, 198.5) 1 month after surgery. Compared with the preoperative values, ACV increased significantly at all time points after surgery (all $p < 0.001$, repeated-measures ANOVA followed by the LSD test). ACV increased continuously from 1 day after surgery to 1 week after surgery ($p < 0.001$). However, the difference in ACV between 1 week and 1 month after surgery was not significant ($p > 0.05$).

As shown in Fig. 3, the changes in ACD showed a similar pattern to the changes in ACV after surgery. ACD was significantly greater at all time points after surgery than before surgery (all $p < 0.001$; repeated-

Table 1 Baseline characteristics

Variables	Value
Age (years)	64.53 ± 8.40 (44–87)
Sex (male/female)	28/23
Operated eye (right/left)	28/23
PVD (yes/no)	33/18
AXL (mm)	24.96 ± 3.01 (20.76–33.88)
ACD (mm)	2.77 ± 0.43 (2.12–3.86)
ACV (mm^3)	146.06 ± 40.95 (91.96–256.09)

Values are presented as means ± standard deviations (range) or number of individuals (n)

PVD Posterior vitreous detachment; *AXL* axial length; *ACD* anterior chamber depth; *ACV* anterior chamber volume

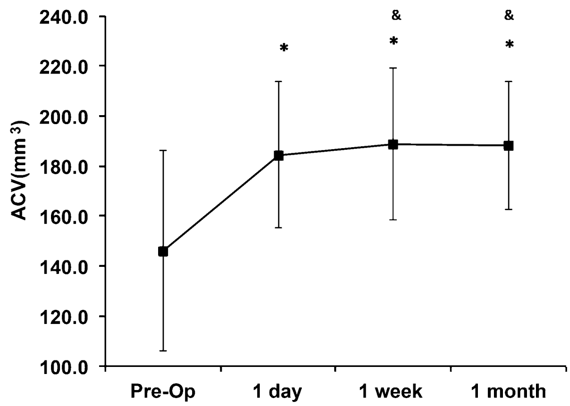

Fig. 1 Changes in anterior chamber volume (ACV) over time. *Significantly different from preoperative ACV ($p < 0.001$, repeated-measures ANOVA followed by the LSD test). &Significantly different from ACV 1 day after surgery ($p < 0.05$, repeated-measures ANOVA followed by the LSD test). Pre-Op = preoperative

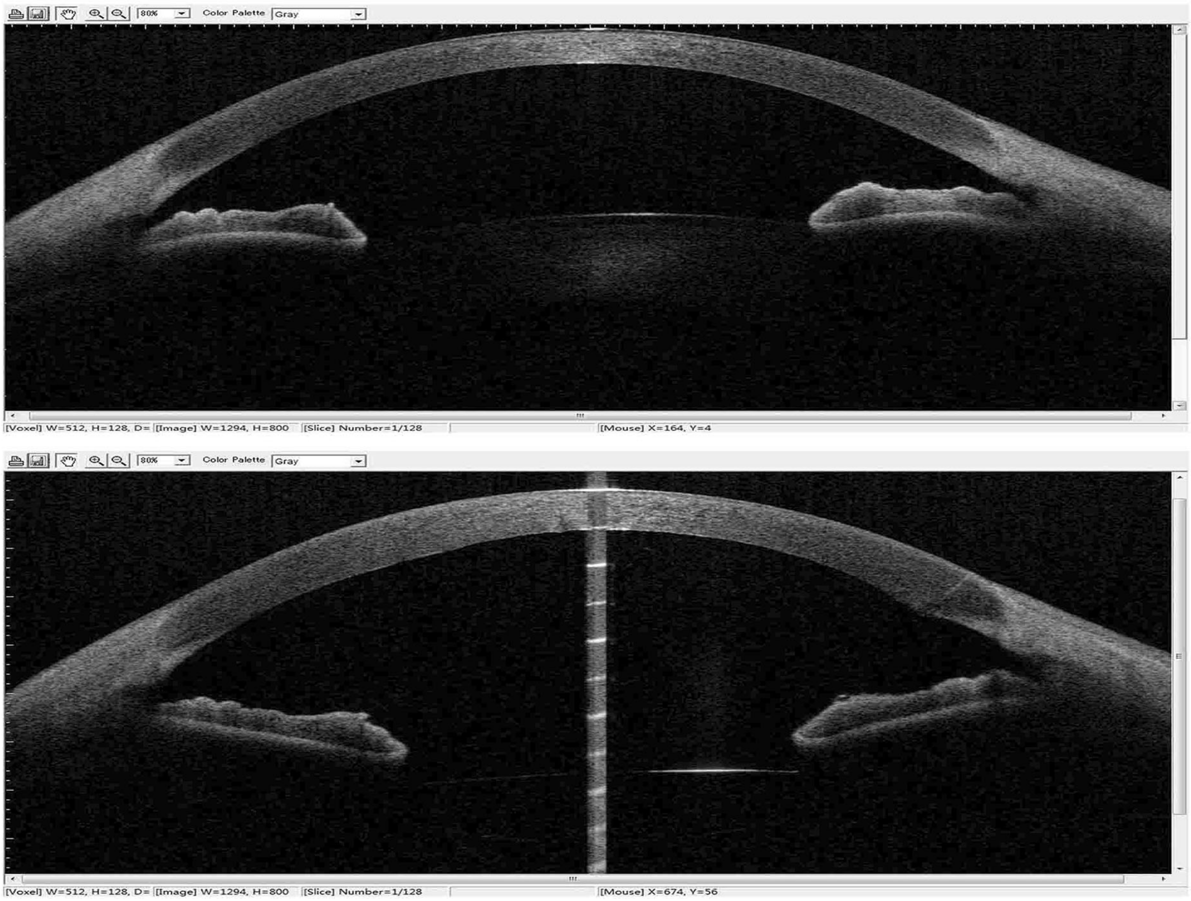

Fig. 2 OCT image of the anterior chamber before and 1 day after cataract surgery

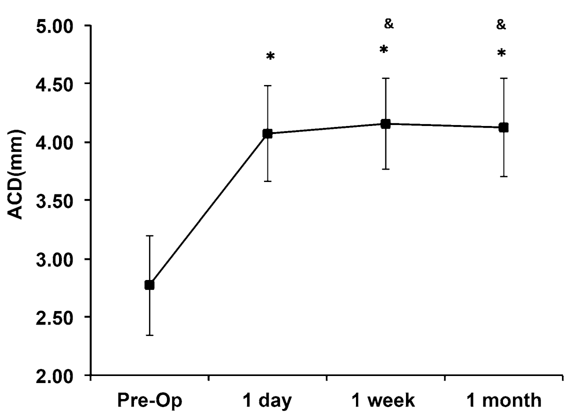

Fig. 3 Changes in anterior chamber depth (ACD) over time. *Significantly different from preoperative ACD ($p < 0.001$, repeated-measures ANOVA followed by the LSD test). [&]Significantly different from ACD 1 day after surgery ($p < 0.05$, repeated-measures ANOVA followed by the LSD test). Pre-Op = preoperative

measures ANOVA followed by the LSD test) (Fig. 2). The value of ACD (4.15 ± 0.40 mm) was also significantly greater 1 week after surgery than 1 day after surgery (4.12 ± 0.41 mm; $p = 0.026$). No difference was observed in ACV between 1 week and 1 month after surgery ($p > 0.05$).

The mean values of all the anterior chamber angle measurements (AOD500, ARA500, TISA500, and TIA500) were significantly greater at all time points after surgery than before surgery (all $p < 0.001$; repeated-measures ANOVA followed by the LSD test) (Table 2). However, no statistically significant differences were detected among the three postoperative time points (all $p > 0.05$; repeated-measures ANOVA followed by the LSD test), as shown in Fig. 4.

Table 2 Mean values for all anterior chamber angle measurements before and after surgery

	AOD500 Mean ± SD 95% CI	ARA500 Mean ± SD 95% CI	TISA500 Mean ± SD 95% CI	TIA500 Mean ± SD 95% CI
Before surgery	0.49 ± 0.25 (0.37, 0.56)	0.26 ± 0.19 (0.22, 0.32)	0.23 ± 0.13 (0.19, 0.24)	34.86 ± 13.04 (31.62, 39.53)
1 day after surgery	0.67 ± 0.18 (0.63, 0.74)	0.32 ± 0.08 (0.29, 0.36)	0.27 ± 0.07 (0.24, 0.29)	49.57 ± 8.17 (47.33, 52.96)
1 week after surgery	0.69 ± 0.19 (0.67, 0.77)	0.32 ± 0.08 (0.30, 0.32)	0.27 ± 0.07 (0.24, 0.28)	48.42 ± 9.50 (46.78, 51.50)
1 month after surgery	0.68 ± 0.11 (0.65, 0.75)	0.31 ± 0.05 (0.29, 0.34)	0.26 ± 0.04 (0.24, 0.29)	48.69 ± 6.21 (46.50, 51.07)

AOD500 Angle opening distance 500; *TISA500* trabecular iris space area 500; *ARA500* angle recess area 500; *TIA500* trabecular iris angle 500. *SD* standard deviation; *95% CI* 95% confidence interval

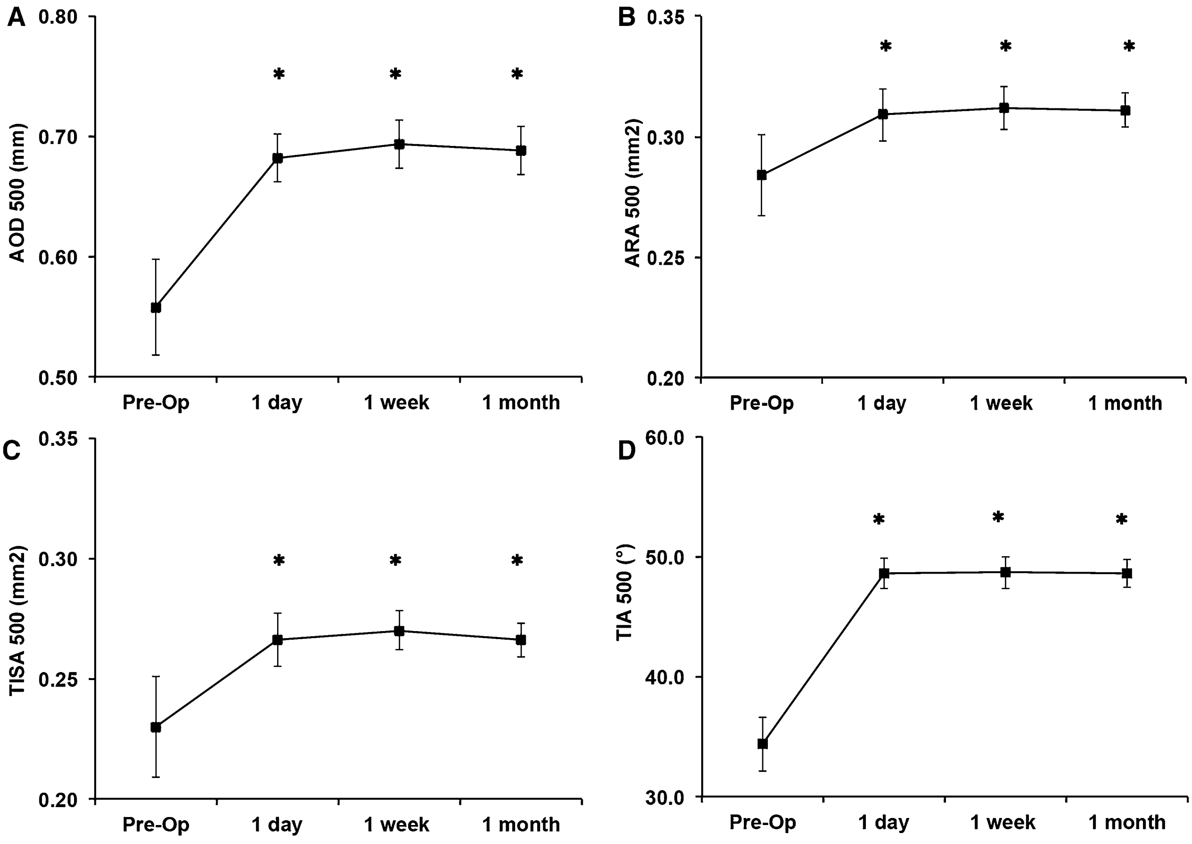

Fig. 4 Changes in the anterior chamber angle measurements (AOD500, ARA500, TISA500, and TIA500) at all time points. *Significantly greater at all time points after surgery than before surgery (all $p < 0.001$; repeated-measures ANOVA followed by the LSD test)

Factors associated with the increase in ACV after surgery

Notably, we found a statistically significant negative correlation between AXL and the change in ACV 1 day after surgery ($r = -0.519$, $p < 0.001$; Pearson's correlation), as shown in Fig. 5. The results of the multiple linear regression analysis are shown in Table 3. After adjustment for age, sex, and the surgically treated eye, the variables AXL and the

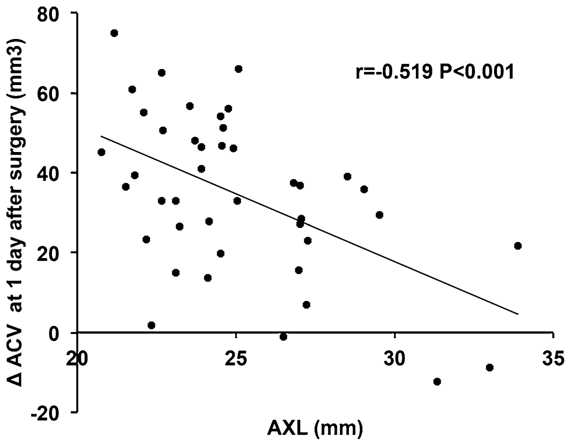

Fig. 5 Relationships between AXL and the change in ACV 1 day after surgery. AXL = axial length; ACV = anterior chamber volume

presence of PVD were significantly associated with the change in ACV 1 day after surgery ($R = 0.602$, $F = 4.099$, $p = 0.005$; multiple linear regression).

We also investigated the relationships between AXL, PVD, and the change in ACV between 1 day after surgery and 1 week after surgery. The majority of patients (43/51, 84.3%) experienced a continuous increase in ACV during the first week after surgery. The patients were then divided into two groups based on an AXL cutoff value of 26 mm. Patients in the longer AXL group had AXL > 26 mm, and those in the shorter AXL group had AXL ≤ 26 mm. The change in ACV from 1 day to 1 week after surgery was 3.71 ± 0.80 mm^3 in the shorter group and 3.81 ± 1.37 mm^3 in the longer group. However, this difference was not significant ($p = 0.9465$; Student's t test). We also analyzed the effect of PVD on the change in ACV from 1 day to 1 week after surgery. The ACV changes were 4.05 ± 0.87 mm^3 in the patients without PVD and 3.58 ± 0.93 mm^3 in the patients with PVD, but the difference was not significant between the two groups ($p = 0.7485$; Student's t test). After adjustment for age, sex, and the surgically treated eye, AXL and the presence of PVD were not significantly associated with the change in ACV between 1 day and 1 week after surgery ($p = 0.652$; multiple linear regression).

Discussion

The position of the IOL, which is closely related to the change in ACV, is associated with fluctuations in the refractive status during the early postoperative period. With recent advances in OCT technology, the novel SS-OCT system can provide rapid and high-resolution images of the anterior chamber, facilitating the accurate calculation of ACV and the other parameters of the anterior chamber [4, 5]. In this study, we used SS-OCT to measure the changes in the anterior segment variables before and after uneventful cataract surgery. We found that ACV and ACD increased during the first week after surgery and were stable thereafter. However, all the anterior chamber angle measurements (AOD500, ARA500, TISA500, and TIA500) remained unchanged after the removal of the cataract. Eyes with a longer AXL and eyes with PVD tended to show less increases in ACV at 1 day after surgery.

Irrigation fluid and BSS are used during cataract surgery and remain after the operation. Studies have shown that eyes with greater AXL tend to have a

Table 3 Multiple linear regression model of the change in ACV between before surgery and 1 day after surgery

Model	Unstandardized coefficients B	Standardized coefficients Beta	t	p value
Age	0.227	0.117	0.862	0.395
Gender	− 2.594	− 0.064	− 0.393	0.696
Operated eye	1.428	0.035	0.239	0.812
AXL	− 2.891	− 0.442	− 2.953	0.006
PVD	− 13.252	− 0.320	− 2.132	0.040

Model: $F = 4.099$, $p = 0.005$

ACV Anterior chamber volume; *AXL* axial length; *PVD* posterior vitreous detachment deeper anterior chamber [6], which may allow more irrigation fluid to flow into the anterior chamber during surgery. However, it is unclear where this fluid goes after surgery. The change in ACV after surgery may answer this question. In this study, we have shown that ACV increased continuously until 1 week after surgery. However, all the anterior chamber angle measurements remained unchanged from 1 day to 1 week after cataract removal. In other words, the increase in ACD accounted for the increase in ACV. ACD is considered to be the clinical and biometric determinant of the actual lens position after cataract surgery [7]. Of course, an increase in ACD suggests that the IOL shifts rearward from 1 day to 1 week after surgery, so the volume of the vitreous cavity will decrease during this period. During surgery, the intraocular pressure could far exceed the normal range under continuous anterior chamber irrigation [8, 9]. Although the zonule is a tenacious filamentous network linking the lens capsule to the ciliary body, it is not impenetrable [10], especially in eyes with a weak zonule. The precise volume of fluid that passes through the zonule is unknown, but it is likely that some irrigation fluid remains in the vitreous cavity for some time after cataract surgery. The fluid in the vitreous cavity could be absorbed via several different pathways, including the retinal capillaries, ciliary body, and anterior chamber angle [11]. The absorption of the fluid present in the choroid might also contribute to the enlargement of the anterior chamber when the fluid balance changes [12, 13]. Consequently, the increase in ACV causes the posterior migration of the IOL plane, which could introduce a hyperopic shift effect [14, 15]. We speculatively attribute the stabilization of ACV seen in this study to the restoration of the balance in fluid absorption about 1 week after cataract surgery.

Eyes with greater AXL tended to show less change in ACV 1 day after surgery compared with eyes with a smaller AXL. Patients with a very long AXL are susceptible to zonular weakness [16], which allows more fluid to enter the posterior compartment of the eyeball and remain in the vitreous cavity. Eyes with a longer AXL have a larger posterior chamber [6], which could provide a reservoir for more irrigation fluid during surgery, so less fluid is retained in the anterior chamber. This explains the smaller increase in ACV on day 1 after surgery in these longer eyes. Because more irrigation fluid remained in the vitreous cavity of patients with longer AXL, the volume of the vitreous cavity changed more when absorption ceased. Consequently, more eyes with longer AXL showed increments in ACV of ≥ 0.1 mm^3 at 1 week after surgery than those with shorter AXL, although the difference was not significant. The presence of PVD might also influence ACV, particularly immediately after surgery. In the eyes of patients with PVD, the lacuna between the vitreous membrane and the internal limiting membrane may form a cavity [17], which can be filled by irrigation fluid. The anterior hyaloid membrane of the vitreous may acquire subtle defects during surgery that allow more irrigation fluid to enter the vitreous cavity [18]. Therefore, the presence of PVD also contributed to the smaller change in ACV 1 day after surgery.

Although a continuous increase in ACV was observed between 1 day after surgery and 1 week after surgery, AXL and the presence of PVD were not significantly associated with the change in ACV. This indicates that fluid absorption reaches a balance 1 week after surgery. However, our small sample may account for the insignificant association between the change in ACV and AXL or the presence of PVD. Moreover, we did not use any cataract scale (e.g., the Lens Opacities Classification System) to classify the cataracts, which would also have affected the change in ACV. Further studies are required to address this issue.

Conclusion

In conclusion, we investigated the changes in ACV after uneventful cataract surgery with SS-OCT. ACV continued to increase during the first week after surgery, but was stable thereafter. Irrigation fluid and BSS are applied during surgery to maintain the anterior chamber, and we speculate that part of this fluid flows into the vitreous cavity through the zonule. Therefore, as well as the removal of the cataract, the consequent absorption of fluid may contribute to the postoperative changes in ACV. Both AXL and PVD were associated with the change in ACV 1 day after surgery, whereas eyes with greater AXL and PVD tended to show less change in ACV 1 week after surgery.

Compliance with ethical standards

Conflict of interest Author Minjie Chen declares that she has no conflict of interest. Author Hailin Hu declares that he has no conflict of interest. Author Wenwen He declares that she has no conflict of interest. Author Yi Lu declares that he has no conflict of interest. Author Xiangjia Zhu declares that she has no conflict of interest.

Research involving human participants and/or animals All procedures in this study involving human participants were performed in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki and its later amendments.

Informed consent Informed consent was obtained from all individual participants included in the study.

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