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Effect of central positioning techniques for anterior capsulotomy in femtosecond laser-assisted cataract surgery on intraocular placement and visual quality

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飞秒激光辅助白内障术中前囊切开中央定位技术对 IOL 植入后位置和视觉质量的影响

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摘要

目的:研究三种不同的前囊切开中央定位技术(瞳孔中心、角膜缘中心和晶状体顶点)在飞秒激光辅助白内障手术(FLACS)后对人工晶状体(IOL)植入位置和视觉质量的影响。

方法:前瞻性研究。纳入 2023-01/12 在安徽医科大学附属爱尔眼科医学中心接受 FLACS 及 ZCB00 非球面 IOL 植入的 36 例 72 眼年龄相关性白内障患者。根据前囊切开的中央定位模式分为三组:瞳孔中心组、角膜缘中心组和晶状体顶点中心组。通过 Casia2 设备评估 IOL 的倾斜和偏心,并对术后视觉质量进行评价。

结果:术后 1 d,瞳孔中心组、角膜缘中心组和顶点中心组的 IOL 倾斜度分别为 3.96°±1.51°、4.63°±1.87°和 3.90°±2.24°(F=1.07, P=0.35);IOL 偏心值分别为 0.21±0.10 mm、0.23±0.16 mm 和 0.21±0.12 mm(F=0.14, P=0.87);总高阶像差分别为 0.32±0.40 μm、0.56±0.61 μm 和 0.53±0.60 μm(F=1.38, P=0.26);彗差值分别为 0.13±0.10 μm、0.16±0.15 μm 和 0.14±0.15 μm(F=0.30, P=0.74)。术后 1 d 的所有结果均无显著差异。术后 3 mo, IOL 倾斜度分别为 5.42°±2.00°、3.96°±1.44°和 3.20°±1.19°(F=12.40, P<0.001);IOL 偏心值分别为 0.33±0.07 mm、0.23±0.11 mm 和 0.21±0.11 mm(F=4.99, P=0.008);总高阶像差分别为 0.67±0.29 μm、0.44±0.37 μm 和 0.42±0.19 μm(F=5.50, P=0.006);彗差值分别为0.21±0.12 μm、0.19±0.12 μm 和 0.12±0.11 μm(F=3.87, P=0.03)。术后 3 mo 的所有结果均具有统计学意义。

结论:在 FLACS 中,采用晶状体顶点作为前囊切开的中央定位模式,可以改善术后 IOL 的稳定性,并减少术后 IOL 的倾斜和偏心。如果术中无法确定晶状体顶点,则建议采用角膜缘中心定位模式。

关键词:飞秒激光;前囊;人工晶状体(IOL);视觉质量;晶状体顶点

Abstract

• AIM: To examine how three distinct central positioning techniques for anterior capsulotomy-pupil center, limbus center, and lens apex - affect intraocular lens (IOL) placement and visual quality following femtosecond laser-assisted cataract surgery (FLACS).

• METHODS: A total of 36 patients (72 eyes) with age-related cataracts who underwent FLACS and ZCB00 aspherical IOL implantation at Aier Eye Hospital Medical Center, Anhui Medical University between January and December 2023 were included in this prospective study. Patients were divided into three groups based on the central positioning mode for anterior capsulotomy: pupil center, limbus center, and lens apex center groups. IOL alignment and displacement were evaluated using the Casia2 device, and the postoperative visual quality was assessed.

• RESULTS: At 1 d postoperatively, the IOL tilt for the pupil, limbus, and apex groups were 3.96°±1.51°, 4.63°±1.87°, and 3.90°±2.24°, respectively (F=1.07, P=0.35); IOL decentration values were 0.21±0.10 mm, 0.23±0.16 mm, and 0.21±0.12 mm, respectively (F=0.14, P=0.87); total higher-order aberrations were 0.32±0.40 μm, 0.56±0.61 μm, and 0.53±0.60 μm, respectively (F=1.38, P=0.26); and coma aberrations values were 0.13±0.10 μm, 0.16±0.15 μm, and 0.14±0.15 μm, respectively (F=0.3, P=

0.74). All results obtained postoperative day 1 did not differ significantly. At 3 mo postoperatively, IOL tilt values were 5.42° ± 2.00°, 3.96° ± 1.44°, and 3.20° ± 1.19°, respectively (F=12.40, P<0.001); IOL decentration values were 0.33±0.07 mm, 0.23±0.11 mm, and 0.21±0.11 mm, respectively (F = 4.99, P = 0.008); total higher-order aberrations were 0.67±0.29 μm, 0.44±0.37 μm, and 0.42±0.19 μm, respectively (F = 5.50, P = 0.006); and coma aberrations values were 0.21±0.12 μm, 0.19±0.12 μm, and 0.12±0.11 μm, respectively (F=3.87, P=0.03). All results obtained 3 mo postoperatively were statistically significant.

• CONCLUSION: Using the lens apex as the central positioning mode for anterior capsulotomy in FLACS improves postoperative IOL stability and reduces postoperative IOL tilt and decentration. If the lens apex cannot be determined intraoperatively, the limbus center-positioning mode is recommended.

• KEYWORDS: femtosecond laser; anterior capsule; intraocular lens(IOL); visual quality; lens apex
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INTRODUCTION

Cataract surgery, which involves replacing a clouded lens with an intraocular lens (IOL), significantly improves eyesight and patients' quality of life. Despite notable advancements in surgical techniques and IOL materials, particularly with the widespread adoption of femtosecond laser technology in recent years, challenges such as IOL tilt and decentration continue to affect visual outcomes and patient satisfaction[1-2]. Excessive tilting and misalignment of the IOL can increase optical aberrations in the human eye, thus diminishing visual clarity following cataract surgery[3]. Previous studies[4-5] have indicated that an IOL decentration of ≥0.4 mm or a tilt of 7° can negatively affect vision and patient satisfaction.

Studies have shown that using a femtosecond laser for capsulotomy offers advantages over manual continuous curvilinear capsulorhexis[6]. In conventional femtosecond laser-assisted cataract surgery (FLACS), the anterior capsulotomy is usually centered on either the pupil or limbus. However, during surgery, uneven pupil dilation or inaccurate limbus positioning due to superior pterygium or arcus senilis can lead to centration inaccuracies, resulting in significant decentration problems.

Recent advancements in swept-source optical coherence tomography (SS-OCT) and intraoperative lens reconstruction techniques, including 3D-OCT image reconstruction of the lens during FLACS, have enabled a more precise evaluation and automatic measurement of IOL tilt and decentration[7-9]. Consequently, using the lens apex as a reference for anterior capsulotomy in femtosecond laser-assisted phacoemulsification has been introduced, theoretically offering improved centration of the anterior capsular opening[10].

Therefore, this study aimed to compare the impact of 3 anterior capsulotomy centration modes-pupil center, limbus center, and lens apex-on the position and visual quality of the IOL after cataract surgery, providing a reference for clinical applications. The findings of this study will guide clinical practice, help optimize anterior capsulotomy techniques in cataract surgery, and improve postoperative visual quality and patient satisfaction.

SUBJECTS AND METHODS

Subjects　This prospective study involved patients with age-related cataracts who underwent FLACS combined with ZCB00 aspherical IOL implantation at Aier Eye Hospital Medical Center, Anhui Medical University from January to December 2023. A total of 72 eyes from 36 patients (16 males and 20 females) were included. The eligibility criteria included: 1) diagnosis of age-related cataract, undergoing FLACS with IOL implantation, adherence to scheduled follow-ups, and willingness to participate in the study-related tests; 2) normal cognitive function and the ability to cooperate during examinations; 3) a natural pupil size of at least 3 mm and a pupil diameter ≥6 mm after dilation; 4) 21 mm ≤ axial length <26 mm. The exclusion criteria were: 1) the presence of other ocular organic diseases affecting vision; 2) intraoperative complications, such as posterior capsule rupture or anterior capsular tear; 3) poor fixation ability and inability to cooperate with examinations; 4) factors affecting lens position, such as a history of ocular trauma or lens dislocation; 5) refractive media opacity affecting Casia2 or IOLMaster700 measurements. All participants provided written informed consent before participation.

Methods　All patients underwent preoperative assessments, including vision tests, intraocular pressure (IOP) measurement, slit-lamp inspection, fundus evaluation, corneal endothelial cell count, ocular B-scan ultrasound, IOL Master 700 biometry, Pentacam anterior segment analysis, and Casia2 examination. Postoperative examinations on the 1 d and 3 mo after surgery included vision tests, IOP measurement, comprehensive optometry, iTrace wavefront aberrometry, and Casia2 examination. All examinations were conducted by the same two technicians on the same day. For lens tilt and decentration measurements under non-dilated conditions, the Casia2 (Tomey, Japan) lens analysis mode was used. The anterior segment images were scanned and processed automatically using built-in software to perform 3D reconstruction analysis and calculate lens tilt and decentration. In the FLACS procedure, the anterior capsulotomy centration mode was divided into 3 groups: pupil center (pupil group), limbus center (limbus group), and lens apex center (apex group). The eyes of 36 patients were numbered based on their hospitalization sequence, and computer-generated random numbers were used to determine the treatment methods for each eye. Each group consisted of 12 right eyes and 12 left eyes. An identical surgeon performed all the procedures using the Victus femtosecond laser system (Bausch & Lomb, Germany), which incorporates real-time OCT scanning and live camera imaging for intraoperative visualization. After laser surgery, incisions and removal of the anterior capsule were conventionally performed using forceps. Lens fragments were removed using a standard phacoemulsification device (Centurion; Alcon, USA). All patients received the same type of monofocal IOL (ZCB00; Johnson & Johnson, USA). This study adhered to the Declaration of Helsinki and received approval from the Ethics Committee of Aier Eye Hospital Medical Center, Anhui Medical University (No.202208).

Statistical Analysis Data analysis was performed using Origin 9.8 statistical software (OriginLab Corporation, Northampton, MA, USA), and graphing was conducted using Origin 9.8 and Python 3.11 software (Python Software Foundation, Wilmington, DE, USA). Continuous variables are represented as mean and standard deviation, while categorical variables are presented as frequencies and percentages. The significance level for statistical tests was set at $\alpha = 0.05$. The Tukey Honestly Significant Difference (HSD) test was used for multiple comparisons after conducting a one-way analysis of variance (ANOVA). The results from the preoperative, 1 d and 3 mo postoperatively were used to plot confidence ellipses and centroids to visualize data distribution and trends. The confidence ellipses display the statistical distribution range of each group, and the centroids mark the concentrated and shifted positions of the data.

RESULTS

This study involved 36 participants (16 males and 20 females) comprising 72 eyes. The average age of the patients was 62.81±9.01 years. Table 1 presents the baseline biometric data of patients in the three groups. The average interval between surgeries for each patient was 14±0 d. Table 2 shows the preoperative baseline data and postoperative visual acuity, IOP, refractive power, lens tilt, decentration, total higher-order aberration, coma, and spherical aberration on 1 d and 3 mo postoperatively. Figures 1A and 1B illustrate the comparisons of tilt and decentration among the different anterior capsulorhexis pattern groups preoperatively and 1 d and 3 mo postoperatively. Figures 1C, 1D, and 1E show the results of total higher-order aberrations, coma aberration, and spherical aberration on 1 d and 3 mo postoperatively across the different anterior capsulorhexis pattern groups.

Figure 2 (A-F) shows the tilt distributions in the pupil, limbus, and apex groups for both eyes of the 36 patients preoperatively, and at 1 d and 3 mo postoperatively. The confidence ellipses and centroid locations of the polar plots revealed that the tilting direction for the right and left eyes in the pupil group shifted from temporally inferior before surgery to temporally superior after surgery. However, the tilting directions for the limbus and apex groups remained consistent at the temporal inferior position both preoperatively and postoperatively. Figure 3 (A-F) illustrates the decentration distribution in the pupil, limbus, and apex groups for both eyes of the 36 patients preoperatively, and at 1 d and 3 mo postoperatively. Analysis of the confidence ellipses and centroid positions in the polar plots showed that the changes in decentration were relatively consistent across the 3 capsulorhexis pattern groups preoperatively and postoperatively.

Across all 72 eyes, tilt measurements showed no statistically significant variation when compared preoperatively, and at 1 d and 3 mo postoperatively ($F = 2.28$, $P = 0.1$). However, decentration outcomes showed a statistically significant difference ($F = 8.12$, $P = 0.0004$). Additional analysis with Tukey's HSD test revealed a statistically significant change in decentration from preoperative to 3 mo postoperatively ($P = 0.0002$); however, no significant difference was found between decentration at 1 d and 3 mo postoperatively ($P = 0.06$). No statistically significant variations were observed in total higher-order aberration; coma aberration or spherical

Table 1 Baseline characteristics of patients included in the study $\bar{x}\pm s$

Variables	Total ($n=72$)	Pupil group ($n=24$)	Limbus group ($n=24$)	Apex group ($n=24$)	F	P
Age (years)	62.81±9.01	64.13±10.66	63.54±9.00	60.75±7.00	0.96	0.39
VC (LogMAR)	1.03±0.53	1.11±0.49	0.95±0.54	1.04±0.56	0.53	0.59
IOP (mmHg)	16.46±2.31	16.00±2.00	16.54±2.50	16.83±2.41	0.80	0.45
ECC (/mm^2)	2516.6±265.45	2538.52±328.23	2535.48±225.54	2475.71±237.25	0.42	0.66
AL (mm)	24.01±1.44	23.93±1.34	24.04±1.29	24.06±1.71	0.06	0.94
Km (D)	44.38±1.69	44.66±1.57	44.60±1.18	43.89±2.14	1.56	0.22
CCT (μm)	529.72±37.16	525.79±39.17	535.79±28.51	527.58±43.09	0.49	0.62
AD (mm)	2.60±0.48	2.64±0.47	2.56±0.41	2.61±0.57	0.15	0.86
LT (mm)	4.37±0.48	4.31±0.54	4.39±0.39	4.39±0.51	0.23	0.80
WTW (mm)	11.40±0.33	11.24±0.37	11.50±0.31	11.45±0.25	4.22	0.02
Tilt (°)	4.79±2.23	4.63±2.47	4.72±2.05	5.03±2.25	0.20	0.82
Decentration (°)	0.18±0.10	0.22±0.10	0.18±0.12	0.15±0.06	3.30	0.05

VC: Visual acuity; IOP: Intraocular pressure; ECC: Endothelial cell count; AL: Axial length; Km: Mean corneal curvature; CCT: Central corneal thickness; AD: Anterior chamber depth; LT: Lens thickness; WTW: White-to-white distance.

Table 2　Follow-up results of patients at 1 d and 3 mo postoperatively　　$\bar{x}\pm s$

Parameters	Total (*n*=72)	Pupil group(*n*=24)	Limbus group(*n*=24)	Apex group(*n*=24)	*F*	*P*
1 Day						
VC (LogMAR)	0.12±0.10	0.13±0.10	0.11±0.11	0.11±0.10	0.45	0.64
Ref (D)	−0.14±0.34	−0.16±0.41	−0.08±0.34	−0.17±0.27	0.49	0.62
IOP (mmHg)	17.34±2.81	16.29±2.18	17.50±3.05	18.25±2.88	3.15	0.05
Tilt (°)	4.16±1.90	3.96±1.51	4.63±1.87	3.90±2.24	1.07	0.35
Decentration (°)	0.22±0.13	0.21±0.10	0.23±0.16	0.21±0.12	0.14	0.87
tHOA (μm)	0.47±0.54	0.32±0.40	0.56±0.61	0.53±0.60	1.38	0.26
Coma (μm)	0.14±0.13	0.13±0.10	0.16±0.15	0.14±0.15	0.30	0.74
Sph (μm)	−0.01±0.15	0.01±0.14	−0.01±0.18	−0.03±0.13	0.33	0.72
3 Month						
VC (LogMAR)	0.12±0.09	0.14±0.08	0.11±0.11	0.10±0.08	0.83	0.44
IOP (mmHg)	16.91±1.60	16.67±1.86	16.96±1.40	17.13±1.54	0.50	0.61
Tilt (°)	4.19±1.80	5.42±2.00	3.96±1.44	3.20±1.19	12.40	<0.001
Decentration (°)	0.26±0.11	0.33±0.07	0.23±0.11	0.21±0.11	4.99	0.008
tHOA (μm)	0.51±0.31	0.67±0.29	0.44±0.37	0.42±0.19	5.50	0.006
Coma (μm)	0.17±0.12	0.21±0.12	0.19±0.12	0.12±0.11	3.87	0.03
Sph (μm)	−0.003±0.104	0.01±0.10	0.01±0.12	−0.03±0.09	0.82	0.44

VC: Visual acuity; Ref: Refraction; IOP: Intraocular pressure; tHOA: Total higher-order aberration; Coma: Coma aberration.

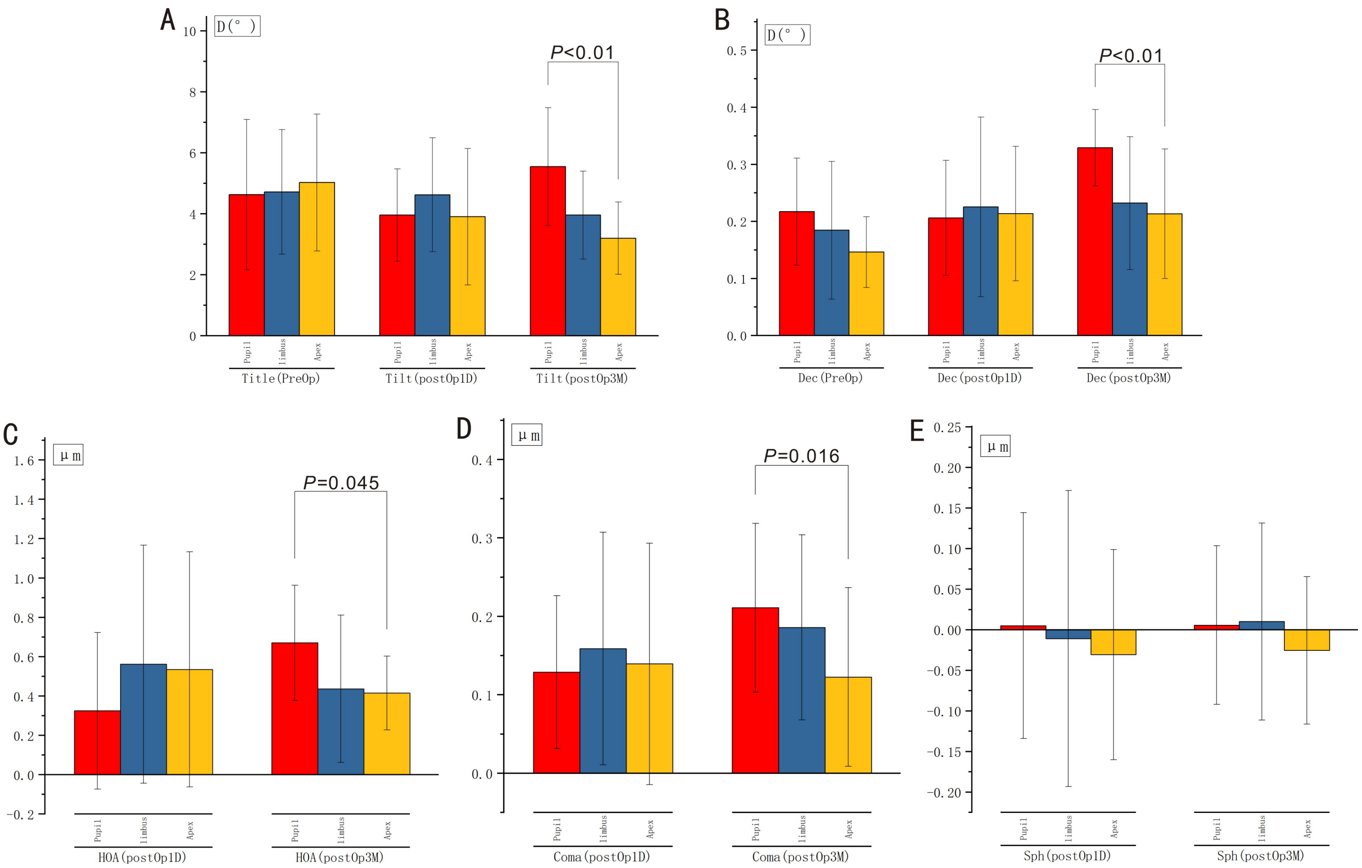

Figure 1　Evaluation of intraocular lens stability and optical aberrations across different capsulorhexis patterns.　A: Evaluating lens tilt across various capsulorhexis pattern groups before surgery, and on 1 d and 3 mo post-surgery; B: Evaluation of lens misalignment across various capsulorhexis pattern groups before surgery, and on 1 d and 3 mo post-surgery; C: Evaluation of overall advanced aberrations across various capsulorhexis pattern groups on 1 d and 3 mo postoperatively; D: Evaluation of coma aberration across various capsulorhexis pattern groups on 1 d and 3 mo postoperatively; E: Evaluation of spherical aberration across various capsulorhexis pattern groups on 1 d and 3 mo postoperatively.

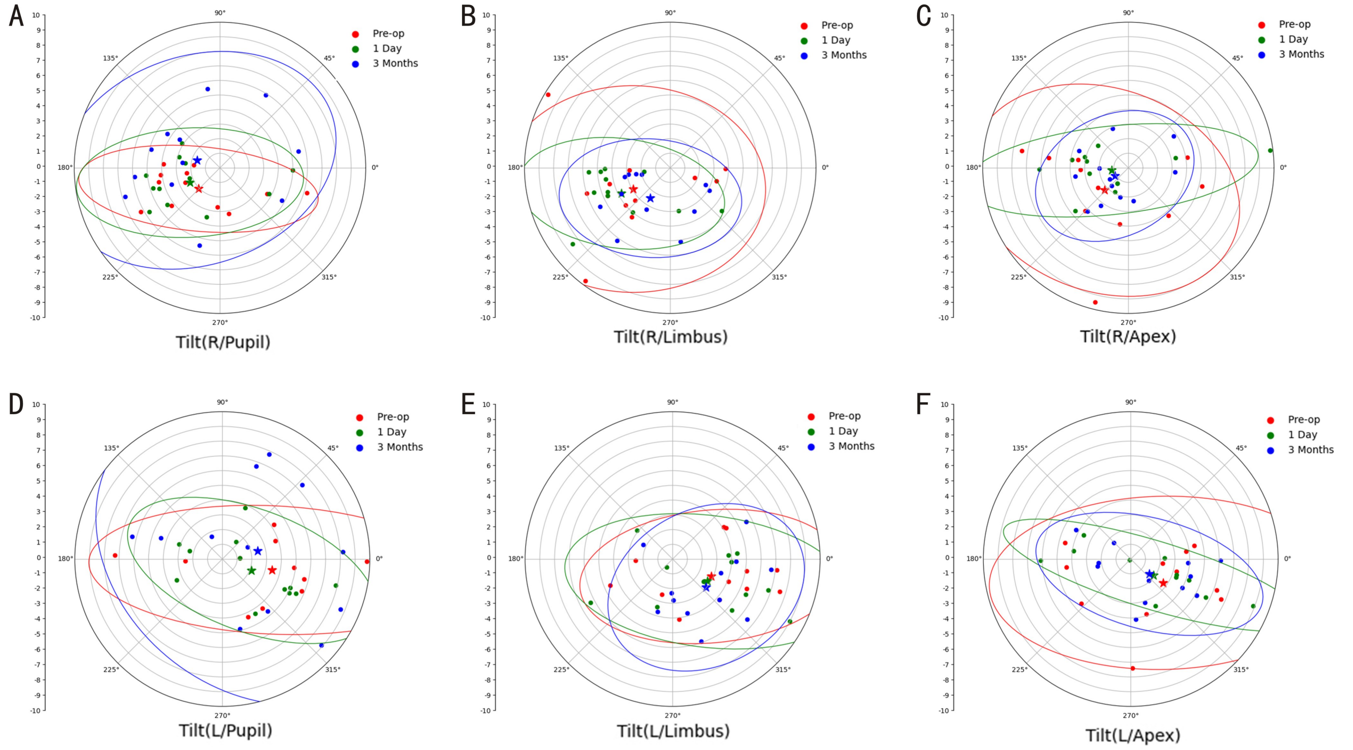

Figure 2 Tilt distribution, confidence ellipses, and centroids of intraocular lenses in right and left eyes across different capsulorhexis central positioning groups before surgery and on 1 d and 3 mo post-surgery. A: Right eye-pupil group; B: Right eye-limbus group; C: Right eye-apex group; D: Left eye-pupil group; E: Left eye-limbus group; F: Left eye-apex group.

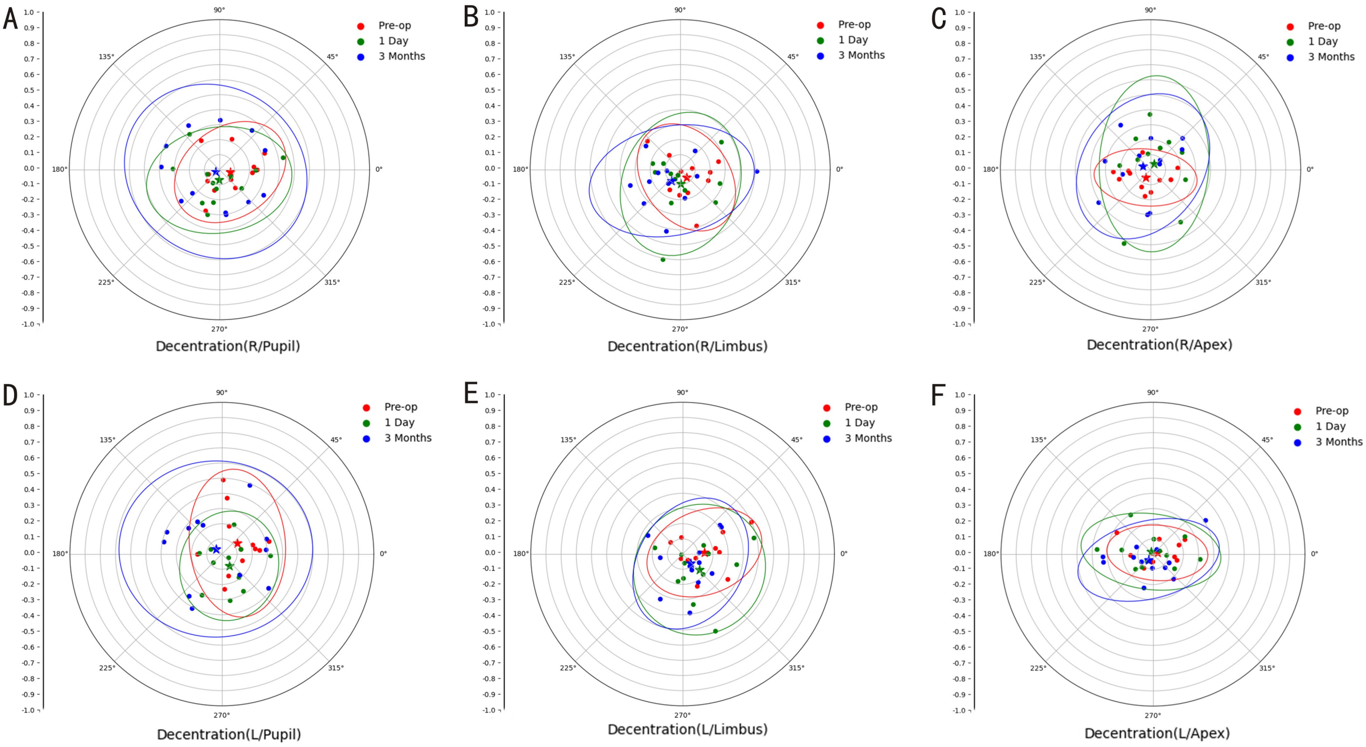

Figure 3 Decentration patterns, confidence ellipses, and centroids of intraocular lenses in right and left eyes across different capsulorhexis central positioning groups before surgery and on 1 d and at 3 mo post-surgery. A: Right eye-pupil group; B: Right eye-limbus group; C: Right eye-apex group; D: Left eye-pupil group; E: Left eye-limbus group; F: Left eye-apex group.

aberration outcomes between 1 d and 3 mo postoperatively (t=-0.45, P=0.65; t=-1.46, P=0.15; t=-0.41, P=0.68).

DISCUSSION

The angle and alignment of IOLs significantly affect vision quality after cataract surgery. FLACS, known for its exceptional accuracy, consistency, and reliability, can minimize postoperative IOL tilt and misalignment. Lee *et al*[11] reported that FLACS reduces the risk of IOL instability. Currently, 3 main centration modes exist for anterior capsulotomy in FLACS: pupil center, limbus center, and lens vertex center. These different modes may affect postoperative IOL stability, especially when there is a significant deviation in capsulotomy centration. Increased tilt and decentration of the IOL can adversely affect visual quality.

Traditional methods, such as Scheimpflug camera images, reflected illumination images, Purkinje images, and SS-OCT (IOL Master 700) images, have relatively low resolution, making precise quantitative measurements of IOL tilt and decentration challenging. Consequently, earlier studies have shown varying outcomes when assessing IOL tilt and displacement[12-13]. Recently, the Casia2 anterior segment OCT scanning technique has been implemented to precisely assess lens and IOL tilt and misalignment. Using integrated software, this technique can assess the tilt and displacement of the lens relative to the corneal topographic axis. Kimura *et al*[14] demonstrated that these results were unaffected by pupil dilation and showed good repeatability. This research found that the tilt and decentration measurements of natural lenses and IOLs using Casia2 aligned with the findings of Hirnschall *et al*[15] and Wang *et al*[12].

Analysis of the preoperative data of the 72 natural lenses and the postoperative data of the same 72 IOLs on 1 d and 3 mo showed no statistically significant difference in the overall tilt measurements. Moreover, the decentration measurements of IOLs on 1 d and 3 mo after surgery revealed no notable statistical variance, suggesting that the tilt and positioning of IOLs remained fairly consistent following FLACS. Further analysis of tilt and decentration among the 3 anterior capsulotomy groups showed that the apex group had significantly less tilt and decentration compared to the pupil group on both 1 d and 3 mo after surgery. This suggests that the capsulotomy mode centered on the lens vertex can improve the postoperative IOL tilt and decentration stability. When SS-OCT cannot accurately achieve a three-dimensional lens reconstruction intraoperatively, the limbus-centered capsulotomy mode should be used. This mode affects postoperative IOL stability similarly to that of the lens vertex-centered mode. The increased tilt and misalignment in the pupil group could be attributed to irregular pupil expansion during the procedure, leading to notable capsulotomy misplacement and causing either partial overlap or uneven contraction between the capsule and IOL. Previous research indicates that while the dimensions and form of capsulotomy minimally affect IOL functionality[16-17], only significantly distorted cases may lead to minor IOL misalignment. However, fibrosis of the capsular bag frequently leads to both horizontal and vertical tilting, especially if capsulotomy fails to fully cover or overlap the lens, which may increase the likelihood of IOL tilt and decentration. Previous studies have indicated that capsular contractions may affect postoperative lens positioning[18-19]. Kato *et al*[20] indicated that capsular tightening may occur as soon as 1 mo after surgery, while Dick and Schultz[21] found that capsular tightening stabilizes within 3 mo. Compared to manual capsulotomy, the FLACS group exhibited lesser capsular contraction and lens position changes at 3 mo post-surgery. Additionally, this research found that, in contrast to the pupil group, the apex group exhibited lesser alterations in IOL tilt and decentration within 3 mo of surgery. However, extended observation is required to evaluate the effects of capsular contraction and other postoperative factors on IOL decentration and tilt. Furthermore, when comparing the tilt and decentration results on 1 d and 3 mo postoperatively, no statistically significant difference was observed between the limbus group and the pupil and apex groups, except for the significant differences observed between the pupil and apex groups. Therefore, although the apex group had a lower tilt and decentration, these differences, though statistically significant, might be relatively small in clinical terms.

Lastly, this study found no overall statistical differences in total higher-order aberrations, coma aberration, and spherical aberration between 3 mo and 1 d postoperatively. However, differences in total higher-order aberrations and coma aberration were observed among the different groups, while no significant differences were found in spherical aberration. Pérez-Gracia *et al*[22] reported that the tilt and misalignment of IOLs significantly affect astigmatism and coma aberration, with a notable influence on horizontal coma aberration. After surgery, the tilt measurements for the limbus and apex groups decreased from their preoperative levels, with decentration remaining consistent. Conversely, the pupil group exhibited an upward trend in both tilt and decentration. Despite the absence of concrete evidence linking greater tilt and decentration in the pupil group to elevated total higher-order aberrations and coma aberration, the possibility of a direct relationship between them remains plausible. A minor tilt and consistent decentration, along with lower postoperative total higher-order aberrations and coma aberration, suggest that using a capsulotomy mode focused on the lens vertex could enhance visual quality and patient satisfaction. This is particularly beneficial for multifocal IOLs, which are highly sensitive to decentration and tilt[23-25].

Based on the analysis of the confidence ellipse range and the changes in centroid position, it can be concluded that the variability in lens tilt and decentration was reduced at 1 d and 3 mo postoperatively compared to preoperative measurements, indicating a positive effect of the FLACS procedure in stabilizing lenstilt and decentration. Notably, the confidence ellipse range for the apex group was smaller at 3 mo postoperatively and comparable to that observed at 1 d postoperatively. Furthermore, an examination of the centroid position changes in IOL tilt and decentration across the 3 groups revealed that the apex group exhibited the least variation in centroid position for both tilt and decentration on 1 d and 3 mo postoperatively. In contrast, the pupil group demonstrated a significant shift in the centroid position of tilt and decentration between 1 d and 3 mo postoperatively. These findings further substantiate the superiority of an anterior capsulotomy incision centered on the lens apex in enhancing the stability of IOL tilt and decentration following FLACS surgery.

This study has limitations: a small sample size of patients with age-related cataracts and conventional axial length, which may affect the generalizability and statistical power of the findings. The short observation period of 3 mo may not capture long-term effects, as suggested by a 2014 study[26] linking decentration with changes in spherical equivalent after a year. We also did not analyze the impact of centration methods on toric and multifocal IOL. Future research should include a larger, more diverse sample and longer follow-up to improve the study's representativeness and reliability.

In conclusion, centering capsulotomy on the lens vertex can enhance the stability of IOL tilt and decentration in FLACS, thereby maintaining patients' visual quality after surgery. For cases where a three-dimensional lens imaging cannot be achieved during FLACS, and the lens vertex cannot be determined, the limbus-centered capsulotomy mode is recommended as it provides better postoperative IOL stability than the pupil-centered mode.

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