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Original Article

A capsular tension ring improves postoperative visual quality in cataract patients by reducing intraocular lens decentration and tilt

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Abstract: Objective: To evaluate the effects of capsular tension ring (CTR) implantation on postoperative visual quality, intraocular lens (IOL) decentration, and tilt, as well as to evaluate its effects on postoperative visual acuity, refraction, IOL positional stability, and other ocular measurements. Methods: This retrospective study included 218 patients with highly myopic cataract (218 eyes). The patients were divided into an experimental group (CTR+IOL, 121 eyes) and a control group (IOL only, 97 eyes) according to surgical protocols. All patients underwent standard cataract surgery, and the experimental group received CTR implantation during surgery. Preoperative and postoperative assessments at 1, 3, and 6 months included best-corrected visual acuity (BCVA), uncorrected visual acuity (UCVA), refraction, IOL decentration, tilt angle, anterior chamber depth (ACD), intraocular pressure (IOP), endothelial cell density (ECD), modulation transfer function (MTF), coma aberration, and visual quality indicators (disability glare index (DLI) and quality of vision index (QVI)). Results: Six months after surgery, ACD, ECD, and improvements in IOL decentration, as well as horizontal and vertical IOL tilt angles and MTF, were significantly better in the experimental group than in the control group (all $P<0.05$). Coma aberration was significantly lower in the experimental group compared to the control group ($P<0.05$). There were no significant differences in visual acuity (BCVA, UCVA) or refractive errors (REs) between the groups. However, the experimental group showed greater improvement in visual quality assessment (DLI, QVI). Additionally, a significant interaction between treatment protocol and age was observed for ECD and horizontal IOL tilt. Conclusion: CTR implantation improves postoperative visual outcomes in highly myopic cataract patients, particularly by reducing IOL decentration and tilt. It enhances visual quality, promotes IOL positional stability, and improves key ocular physiological indicators.

Keywords: Capsular tension ring, cataract surgery, visual quality, IOL decentration, IOL tilt, postoperative outcomes

Introduction

Cataract is a common ocular disease and remains a leading cause of blindness, particularly among the elderly [1]. According to data from WHO, the global burden of cataract is expected to rise further due to population aging and increased life expectancy [2]. In addition to visual impairment, cataract can adversely affect patients' quality of life and may be associated with psychological distress and reduced social functioning.

Cataract surgery is currently the most effective and widely performed treatment for this condition. The procedure restores vision by removing the opacified crystalline lens and inserting an intraocular lens (IOL) [3]. Advancements in IOL design and optimization of surgical technique have significantly improved surgery success rate and postoperative visual quality. For example, Zhong et al. [4] compared femtosecond laser arcuate keratotomy with toric IOL implantation for astigmatism correction, highlighting the diversification of surgical techniques. Nevertheless, different IOL implantation systems may influence incision size and postoperative visual outcomes, underscoring the importance of surgical technique optimization. Recent progress in IOL technology has been remarkable [5]. Singh et al. [6] reported that a novel aspherical hydrophobic acrylic monofocal

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IOL provides excellent visual and refractive outcomes. Furthermore, digital marking technology in toric IOL implantation has been shown to effectively reduce postoperative cylindrical error and improve uncorrected visual acuity [7]. Oshika et al. [8] evaluated 8-year outcomes of toric IOL implantation and found differences related to astigmatism types over time, emphasizing the need for long-term evaluation.

As case complexity increases, technical challenges of surgery also increases. Evidence suggests that toric IOL implantation is effective in improving visual outcomes in patients with concurrent cataract and glaucoma [10]. Pellegrini et al. [11] further demonstrated that toric IOL implantation can reduce refractive astigmatism and optimize visual outcomes in eyes undergoing corneal transplantation. However, such complex cases demand higher levels of surgical expertise and careful selection of instrumentation. Despite advances in surgical techniques, postoperative IOL decentration and tilt remain unavoidable, which may lead to refractive errors and suboptimal visual outcomes. The capsular tension ring (CTR) has been introduced as an adjunct device to enhance capsular bag stability, thereby reducing IOL decentration and tilt and improving postoperative visual quality.

Multiple factors influence cataract surgical outcomes. Shoshi et al. [9] reported that preoperative visual acuity, IOL type, and surgeon experience are significant factors affecting refractive outcome. Therefore, optimal surgical results require comprehensive consideration of all influencing factors.

This study aims to systematically evaluate the effects of CTR implantation on postoperative visual quality in cataract patients, with particular focus on its role in reducing IOL decentration and tilt. Using a retrospective comparative design, we compared outcomes between a CTR implantation group and a conventional surgery control group.

Materials and methods

Sample size calculation

Based on a randomized controlled trial published in *Curr Eye Res* [12], which evaluated the impact of CTR implantation on rotational stability of multifocal toric IOLs, the IOL rotation angle (degrees) at 3 months postoperatively was selected as the primary endpoint in this study. Sample size was calculated using methods for comparing means between two independent groups.

According to the between-group differences observed in the high myopia subgroup of the referenced study and trends reported in similar literature, the expected difference in rotation angle (Δ) between CTR and non-CTR groups was set at 1.0° (clinically meaningful: each 1° of IOL rotation corresponds to an approximate 3.3% loss of astigmatic correction), with pooled standard deviation (SD) of 2.5° (based on rotational stability data of similar plate-haptic multifocal toric IOLs). With a two-sided significance level of α=0.05 and a statistical power (1-β) of 80%, the required sample size was calculated to be 99 patients per group. Considering a potential 10% loss to follow-up or dropout rate, the final sample size was adjusted to 109 patients per group, resulting in a total of 218 eyes.

Sample collection

This retrospective analysis included 109 cataract patients (218 eyes) who received treatment at our hospital from November 2022 to December 2024. Patients were divided into an experimental group (CTR+IOL, 121 eyes) and a control group (IOL only, 97 eyes) based on different treatment protocols. This study was approved by the Medical Ethics Committee of Yulin City Hospital of Traditional Chinese Medicine (Yulin, Shaanxi Province, China).

Inclusion and exclusion criteria

Inclusion criteria: Age ≥18 years; diagnosis of unilateral cataract; high myopia with axial length >26.5 mm and spherical equivalent refraction ≥-6.00 D; fulfillment of the indications for cataract surgery [13]; no evidence of lens subluxation on preoperative slit-lamp examination; complete clinical data.

Exclusion criteria: other severe systemic or ocular diseases in addition to high myopia and cataract; abnormal preoperative IOP, to exclude glaucoma and other pressure-related complications; a history of long-term use of medications that could affect ocular status; pregnancy or lactation.

Treatment protocols

Control group: standard phacoemulsification cataract surgery was performed without the use of a CTR. A 2.2 mm clear corneal incision was made, followed by the formation of a side-port incision using a keratome. Viscoelastic material was then injected into the anterior chamber. Afterwards, continuous curvilinear capsulorhexis (CCC), hydrodissection, and phacoemulsification were performed, followed by aspiration of lens nucleus and cortical material. A hydrophilic acrylic, aspheric, monofocal IOL (C-flex 970C, Rayner, United Kingdom) was then implanted into the capsular bag through an IOL injector. IOL power was calculated using the Barrett Universal II formula based on biometric measurements obtained with the IOLMaster 700. At the end of the procedure, wound integrity was confirmed to ensure a watertight seal.

Experimental group: The surgical procedure was identical to that of the control group, with the addition of CTR implantation. A standard one-piece PMMA capsular tension ring (Type 14C, Morcher, Germany) was selected based on preoperative white-to-white (WTW) distance measured using the IOLMaster 700: a 10.0 mm CTR was used for WTW ≤11.5 mm, and a 12.0 mm CTR for WTW >11.5 mm. The CTR was cautiously inserted into the capsular bag through the main incision using an injector to ensure capsular stability and maintain optimal IOL positioning.

Postoperatively, all patients received standard topical medications, including antibiotics, corticosteroids, and lubricating agents. All patients were followed up at scheduled intervals to evaluate clinical outcomes (Figure S1).

Detection indicators and instrumentation

In this study, multiple ophthalmic instruments were used to ensure accurate assessments during the preoperative and post-operative periods. Anterior segment examinations were conducted using the slit-lamp microscopy (SLK-KD, Chongqing Kanghua). The IOL-master700 (Carl Zeiss, Germany) was used to measure ocular biometric indicators, including axial length (AL), anterior chamber depth (ACD), and corneal curvature. IOP was measured using the NT-530 (Nidek, Japan). Objective refraction was assessed using an automated refractometer (CP-770, Nidek, Japan). In addition, an INFINITI (Alcon, USA) device was employed for phacoemulsification, and a VOLK90D (Volk, USA) lens was used for fundus examination under slit-lamp biomicroscopy. Optical coherence tomography (OCT) imaging was performed using the CIRRUS HD-OCT 5000 (Carl Zeiss Meditec, Germany), while swept-source OCT (SS-OCT) measurements were obtained using the TOP-SIGMA 1000 system (Tomey/Tupai, China). All instruments were operated according to standardized protocols to ensure the reliability and reproducibility of the measurements.

Clinical data collection

Clinical data were sourced from outpatient follow-up records and the electronic medical record (EMR) system. Collected baseline demographic data included age, sex, body mass index (BMI), and history of hypertension and diabetes mellitus. Ocular parameters included white-to-white distance, AL, lens thickness, corneal curvature, and ACD. Visual function data included preoperative and postoperative best-corrected visual acuity (BCVA) and uncorrected visual acuity (UCVA), as well as postoperative refraction and changes of refractive error. Postoperative clinical assessments included IOP, endothelial cell density (ECD), and retinal examination findings. Postoperative complications, including posterior capsule opacification, retinal detachment, and cystoid macular edema were also recorded. Visual quality was also evaluated at 1 month postoperatively, including the disability glare index (DLI) [14] and quality of vision index (QVI) [15]. In addition, postoperative quality of life (QoL) was assessed using standardized QoL questionnaires to evaluate overall patient satisfaction and functional outcomes.

Outcome measurements

Primary outcomes: The primary outcomes included postoperative changes in visual acuity, refraction, IOL decentration and tilt, as well as the incidence of postoperative complications. Visual acuity outcomes were assessed using BCVA and UCVA measured preoperatively and at 1, 3, and 6 months postoperatively. Postoperative refraction was compared to preoperative target refraction to assess refractive outcomes, and the effect of CTR implantation on refractive error was further analyzed. IOL

Table 1. Comparison of baseline characteristics between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	t/Z/χ^2 Value	*P* Value
Age (years)	60.00 [56.00, 65.00]	61.00 [58.00, 66.00]	1.115	0.265
BMI (kg/m^2)	23.62±1.74	23.39±1.71	-0.975	0.331
White-to-white distance (mm)	12.27±1.07	12.28±0.95	0.082	0.934
Axial length (mm)	30.40±2.08	30.23±2.28	-0.582	0.561
Lens thickness (mm)	3.91 [3.56, 4.19]	3.88 [3.53, 4.24]	0.265	0.791
Gender (M/F)	44/53	52/69	0.124	0.724
Affected side (OD/OS)	56/41	64/57	0.51	0.475
Hypertension history (Y/N)	24/73	38/83	1.174	0.279
Diabetes history (Y/N)	19/78	22/99	0.07	0.792
Smoking history (Y/N)	47/50	67/54	1.033	0.309
Alcohol consumption history (Y/N)	20/77	22/99	0.206	0.65

Note: BMI, Body Mass Index; OD = right eye, OS = left eye; Y = yes, N = no.

decentration and tilt angles were assessed at 1 day, 1 month, 3 months, and 6 months postoperatively to evaluate IOL positional stability.

Secondary outcomes: Changes in ocular indicators, visual quality metrics, and postoperative QoL scores were recorded. Ocular parameters (e.g., ACD, IOP, ECD) were measured at 1, 3, and 6 months postoperatively. Visual quality was assessed using the modulation transfer function (MTF) and coma aberration assessed at 1 day, 1 month, 3 months, and 6 months postoperatively. Visual quality (DLI and QVI), was recorded preoperatively and at 1 month postoperatively.

Statistical analysis

SPSS version 25.0 (IBM Corporation) and R version 4.3.3 were used for statistical analyses. Quantitative data were first tested for normal distribution using Kolmogorov-Smirnov (K-S) tests. Normally distributed data were expressed as mean ± standard deviation (SD) and compared between groups using independent samples t-tests. Non-normally distributed data were expressed as median (interquartile range, IQR) and compared between groups using Mann-Whitney U tests. For repeated measurements over time, repeated-measures analysis of variance (ANOVA) was performed to evaluate within-group and between-group differences, followed by Bonferroni correction or multiple comparisons. Categorical variables were compared using the chi-square test. Interaction analyses were conducted using R Software to evaluate the potential interaction between treatment protocol and age on selected outcomes. All statistical tests were two-sided, and a *P* value <0.05 was considered significant.

Results

Comparison of baseline characteristics between the two groups

No significant differences were observed between the two groups in terms of age, sex, BMI, white-to-white distance, AL, lens thickness, affected side, history of hypertension, diabetes, smoking, or alcohol consumption (all P>0.05; **Table 1**).

Comparison of pre- and postoperative visual acuity changes between the two groups

As shown in **Table 2**, no significant differences were observed between the two groups in BCVA or UCVA at any time points (all P>0.05).

Within-group analysis demonstrated that both BCVA and UCVA improved significantly at 1-month postoperatively compared to preoperative values (P<0.05), with further improvement observed at 3 months compared to 1 month (P<0.05). However, no significant differences were found between 3 and 6 months postoperatively (P>0.05).

Comparison of pre- and postoperative refraction and refractive error between the two groups

As shown in **Table 3**, no significant differences were observed between the two groups in refraction or refractive error at any evaluated time point (all P>0.05).

Table 2. Comparison of pre- and postoperative visual acuity changes between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	$t/Z/\chi^2$ Value	*P* Value
Preoperative BCVA	1.09 [0.48, 1.80]	1.17 [0.64, 1.75]	0.372	0.71
1-month postoperative BCVA	0.34 [0.17, 0.59][a]	0.47 [0.18, 0.74][a]	1.505	0.132
3-month postoperative BCVA	0.37 [0.18, 0.55][a]	0.32 [0.14, 0.50][a,b]	1.019	0.308
6-month postoperative BCVA	0.26 [0.11, 0.49][a,b]	0.27 [0.13, 0.53][a,b]	0.458	0.647
Preoperative UCVA	1.57±0.11	1.57±0.11	-0.244	0.808
1-month postoperative UCVA	0.72±0.05[a]	0.72±0.05[a]	-0.384	0.702
3-month postoperative UCVA	0.70±0.05[a,b]	0.69±0.05[a,b]	-1.596	0.112
6-month postoperative UCVA	0.67±0.03[a,b,c]	0.67±0.04[a,b,c]	0.206	0.837

Note: [a]P<0.05, compared to preoperative; [b]P<0.05, compared with 1-month postoperative; [c]P<0.05, compared to 3-month postoperative. BCVA, Best Corrected Visual Acuity; UCVA, Uncorrected Visual Acuity.

Table 3. Comparison of pre- and postoperative refraction and refractive error between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	$t/Z/\chi^2$ Value	*P* Value
Preoperative target refraction (D)	-3.00±0.74	-2.84±0.61	-1.659	0.099
1-month postoperative refraction (D)	-2.61±0.74[a]	-2.53±0.74[a]	-0.734	0.464
3-month postoperative refraction (D)	-2.51±0.66[a]	-2.56±0.72[a]	0.528	0.598
6-month postoperative refraction (D)	-2.48±0.74[a]	-2.36±0.72[a,c]	-1.266	0.207
1-day postoperative refractive error (D)	0.84 [0.40, 1.57]	1.00 [0.47, 1.55]	1.098	0.272
1-month postoperative refractive error (D)	0.97 [0.54, 1.65]	0.84 [0.43, 1.61]	1.123	0.262
3-month postoperative refractive error (D)	1.06 [0.43, 1.74]	1.01 [0.54, 1.84]	0.681	0.496
6-month postoperative refractive error (D)	0.88 [0.47, 1.49]	1.07 [0.47, 1.77]	1.463	0.144

Note: [a]P<0.05, compared to preoperative or 1-day postoperative; [c]P<0.05, compared to 3-month postoperative. D, Diopter.

Within-group comparisons showed that postoperative refraction improved significantly over time, with significant differences observed between preoperative and 1-month values, as well as between 1- and 3-month, and 3- and 6-month time points (all P<0.05). However, refractive error remained stable over time, showing no significant changes across all assessment time points in either group (P> 0.05).

Comparison of pre- and postoperative ocular indicator changes between the two groups

No significant differences were observed between the two groups in ACD (P=0.098), IOP (P=0.050), or ECD (P=0.305) at baseline.

Postoperatively, ACD increased significantly in both groups at 1 month, 3 months, and 6 months, with more pronounced improvements in the experimental group (all P<0.001). In contrast, no significant between-group differences were found in IOP at 1 month, 3 months, or 6 months postoperatively. Similarly, ECD did not differ significantly between groups at any postoperative time point (all P>0.05).

Within-group comparisons showed that ACD increased significantly, while IOP and ECD decreased significantly, at 1 month compared to preoperative values, with further increase/decrease at 3 months and 6 months (all P<0.05, **Table 4**).

Comparison of postoperative IOL decentration and tilt between the two groups

Postoperative changes in IOL decentration and tilt were analyzed at 1 day, 1 month, 3 months, and 6 months after surgery (**Table 5**). Representative anterior segment images demonstrating postoperative IOL position and centration in both groups are presented in Figure S2.

At 1 day and 1 month postoperatively, there were no significant differences between the two groups in IOL decentration, horizontal tilt,

Table 4. Comparison of pre- and postoperative ocular indicator changes between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	t/Z/χ^2 Value	*P* Value
Preoperative ACD (mm)	3.48±0.48	3.39±0.33	-1.661	0.098
1-month postoperative ACD (mm)	4.49±0.32[a]	4.89±0.38[a]	8.334	<0.001
3-month postoperative ACD (mm)	4.65±0.39[a,b]	4.87±0.30[a]	4.734	<0.001
6-month postoperative ACD (mm)	4.67 [4.46, 4.93][a,b]	4.93 [4.58, 5.08][a]	3.61	<0.001
Preoperative IOP (mmHg)	16.72 [15.06, 18.11]	17.48 [15.47, 18.73]	1.961	0.05
1-month postoperative IOP (mmHg)	13.78±2.90[a]	14.26±1.38[a]	1.603	0.11
3-month postoperative IOP (mmHg)	13.33 [11.70, 15.31][a]	14.02 [13.17, 15.14][a]	1.791	0.073
6-month postoperative IOP (mmHg)	15.11±2.51[a,b,c]	15.08±1.90[a,b,c]	-0.113	0.91
Preoperative ECD (cells/mm^2)	2768.54±85.51	2770.80±89.09	1.028	0.305
1-month postoperative ECD (cells/mm^2)	2199.19±64.37[a]	2200.55±48.68[a]	0.179	0.858
3-month postoperative ECD (cells/mm^2)	2104.47±67.07[a,b]	2114.67±61.83[a,b]	1.165	0.245
6-month postoperative ECD (cells/mm^2)	2022.58±88.55[a,b,c]	2031.38±79.17[a,b,c]	0.774	0.44

Note: [a]P<0.05, compared to preoperative; [b]P<0.05, compared to 1-month postoperative; [c]P<0.05, compared to 3-month postoperative. ACD, Anterior Chamber Depth; IOP, Intraocular Pressure; ECD, Endothelial Cell Density.

Table 5. Comparison of IOL decentration and tilt angles between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	t/Z/χ^2 Value	*P* Value
1-day postoperative IOL decentration (mm)	0.30 [0.23, 0.34]	0.28 [0.23, 0.33]	1.378	0.168
1-month postoperative IOL decentration (mm)	0.40±0.11[a]	0.39±0.09[a]	-0.765	0.445
3-month postoperative IOL decentration (mm)	0.51±0.11[a,b]	0.45±0.08[a,b]	-4.455	<0.001
6-month postoperative IOL decentration (mm)	0.60±0.10[a,b,c]	0.49±0.08[a,b,c]	-9.274	<0.001
1-day postoperative IOL horizontal tilt (°)	0.90±0.51	1.01±0.55	1.569	0.118
1-month postoperative IOL horizontal tilt (°)	3.02±0.58[a]	3.02±0.55[a]	0.091	0.928
3-month postoperative IOL horizontal tilt (°)	3.63±0.28[a,b]	3.39±0.51[a,b]	-4.111	<0.001
6-month postoperative IOL horizontal tilt (°)	4.75±0.80[a,b,c]	4.26±0.74[a,b,c]	-4.647	<0.001
1-day postoperative IOL vertical tilt (°)	0.78 [0.41, 1.06]	0.69 [0.42, 1.09]	0.651	0.515
1-month postoperative IOL vertical tilt (°)	3.06±0.53[a]	3.13±0.51[a]	1.019	0.309
3-month postoperative IOL vertical tilt (°)	4.13±0.48[a,b]	3.73±0.43[a,b]	-6.447	<0.001
6-month postoperative IOL vertical tilt (°)	4.90±0.49[a,b,c]	4.65±0.58[a,b,c]	-3.495	<0.001

Note: [a]P<0.05, compared to 1-day postoperative; [b]P<0.05, compared with 1-month postoperative; [c]P<0.05, compared to 3-month postoperative. IOL, Intraocular Lens.

or vertical tilt (all P>0.05). At 3 months postoperatively, the experimental group demonstrated significantly reduced IOL decentration, horizontal tilt, and vertical tilt compared with the control group (all P<0.001), indicating improved IOL centration and positional stability in the experimental group. At 6 months postoperatively, the experimental group maintained superior outcomes in all indicators. IOL decentration, horizontal tilt, and vertical tilt were all significantly lower than in the control group (all P<0.001), indicating sustained IOL positional stability.

Within-group comparisons demonstrated progressive increases in IOL decentration and tilt over time in the control group, whereas the experimental group showed more stable values, particularly between 3 and 6 months. These results confirm that CTR implantation during cataract surgery effectively reduces IOL decentration and tilt, enhancing postoperative optical outcomes.

Comparison of postoperative visual quality indicators between the two groups

Postoperative visual quality indicators, including MTF and coma aberration, were compared between the two groups at various postoperative time points (**Table 6**). No significant differences were observed in MTF or coma aberration between the groups at 1 day, 1 month, or 3 months postoperatively (all P>0.05). At 6 months postoperatively, MTF was significantly higher in the experimental group than in con-

Table 6. Comparison of postoperative visual quality indicators between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	$t/Z/\chi^2$ Value	*P* Value
1-day postoperative MTF	0.34±0.12	0.35±0.13	0.745	0.457
1-month postoperative MTF	0.61±0.11[a]	0.58±0.12[a]	-1.677	0.095
3-month postoperative MTF	0.67±0.10[a,b]	0.64±0.14[a,b]	-1.802	0.073
6-month postoperative MTF	0.67 [0.59, 0.73][a,b,c]	0.74 [0.67, 0.81][a,b,c]	5.379	<0.001
1-day postoperative coma aberration (μm)	0.34±0.09	0.35±0.10	0.567	0.571
1-month postoperative coma aberration (μm)	0.49±0.12[a]	0.49±0.10[a]	0.066	0.948
3-month postoperative coma aberration (μm)	0.53±0.12[a,b]	0.54±0.11[a,b]	0.201	0.841
6-month postoperative coma aberration (μm)	0.68±0.13[a,b,c]	0.55±0.19[a,b]	-5.791	<0.001

Note: [a]P<0.05, compared to 1-day postoperative; [b]P<0.05, compared with 1-month postoperative; [c]P<0.05, compared to 3-month postoperative. MTF, Modulation Transfer Function.

Table 7. Comparison of pre- and postoperative visual quality between the two groups

Variable	Control Group (n=97)	Experimental Group (n=121)	Statistic	*P* Value
Preoperative DLI	1.51±0.59	1.53±0.63	0.256	0.798
1-month postoperative DLI	8.01 [6.87, 8.87][a]	9.10 [8.32, 10.11][a]	6.479	<0.001
Preoperative QVI	1.14±0.30	1.13±0.35	-0.245	0.807
1-month postoperative QVI	3.50±0.55[a]	4.80±0.45[a]	19.235	<0.001

Note: [a]P<0.05, compared to preoperative. DLI, Disability Glare Index; QVI, Quality of Vision Index.

trols (P<0.001), and coma aberration was significantly lower in the experimental group than in controls (P<0.001). Within-group analysis showed that MTF in the experimental group increased significantly from 3 to 6 months, whereas coma aberration remained stable over the same period.

Comparison of pre- and postoperative subjective visual quality between the two groups

Subjective visual quality, assessed using DLI and QVI showed no significant differences between groups at baseline (DLI: P=0.798; QVI: P=0.807). At 1-month postoperatively, both DLI (P<0.001) and QVI (P<0.001) improved significantly compared to preoperative values, with more pronounced improvement observed in the experimental group than in the control group (**Table 7**).

Comparison of various indicators in patients aged <60 years: preoperative vs. postoperative 6 months

A subgroup analysis was performed in patients aged <60 years to compare baseline characteristics and 6-month postoperative outcomes (**Table 8**). Baseline variables, including BMI (P=0.982), white-to-white distance (P=0.799), axial length (P=0.373), lens thickness (P=0.975), sex (P=0.804), affected eye (P=0.546), hypertension history (P=0.399), diabetes history (P=0.708), smoking history (P=0.062), and alcohol consumption history (P=0.717), showed no significant differences between groups.

At 6 months postoperatively, no significant differences were observed between groups in visual outcomes, including BCVA (P=0.519), UCVA (P=0.190), refraction (P=0.429), or refractive error (P=0.625). However, significant between-group differences were observed in several ocular parameters, including ACD (P=0.003), IOL vertical tilt (P=0.005), IOL decentration (P<0.001), and IOL horizontal tilt (P=0.016), all favoring the experimental group. In addition, visual quality indicators at 6 months, including MTF (P<0.001) and coma aberration (P<0.001), showed significant improvement in the experimental group compared with the control group.

Comparison of various indicators in patients aged ≥60 years: preoperative vs. 6 postoperative 6 months

Subgroup analysis conducted in patients aged ≥60 years showed that there were no significant differences between groups in age (P=0.866), BMI (P=0.208), white-to-white distance (P=0.830), axial length (P=0.927), lens

Table 8. Comparison of baseline data and postoperative 6-month indicators in patients aged <60 years

Variable	Control Group (n=45)	Experimental Group (n=47)	t/Z/χ^2 Value	*P* Value
Age (years)	56.00 [54.00, 58.00]	56.00 [54.50, 59.00]	0.844	0.399
BMI (kg/m^2)	23.56±1.84	23.56±1.61	0.023	0.982
White-to-white distance (mm)	12.20±1.26	12.26±0.97	0.255	0.799
Axial length (mm)	30.64±1.85	30.22±2.56	-0.896	0.373
Lens thickness (mm)	3.93 [3.53, 4.14]	3.82 [3.42, 4.24]	0.031	0.975
Gender (M/F)	18/27	20/27	0.062	0.804
Affected side (OD/OS)	24/21	28/19	0.364	0.546
Hypertension history (Y/N)	13/32	10/37	0.71	0.399
Diabetes history (Y/N)	8/37	7/40	0.14	0.708
Smoking history (Y/N)	20/25	30/17	3.482	0.062
Alcohol consumption history (Y/N)	11/34	10/37	0.131	0.717
6-month postoperative ACD	4.65±0.35	4.87±0.32	3.069	0.003
6-month postoperative BCVA	0.20 [0.10, 0.44]	0.27 [0.13, 0.56]	0.645	0.519
6-month postoperative IOL vertical tilt (°)	5.01 [4.67, 5.23]	4.73 [4.31, 5.00]	2.789	0.005
6-month postoperative IOL decentration (mm)	0.61±0.09	0.47±0.08	-7.7	<0.001
6-month postoperative IOL horizontal tilt (°)	4.55±0.72	4.17±0.74	-2.455	0.016
6-month postoperative UCVA	0.66±0.04	0.67±0.04	1.322	0.19
6-month postoperative MTF	0.65±0.11	0.75±0.10	4.461	<0.001
6-month postoperative coma aberration (μm)	0.68±0.13	0.53±0.18	-4.666	<0.001
6-month postoperative ECC (cells/mm^2)	2019.00 [1955.00, 2068.00]	2081.00 [2033.00, 2105.00]	3.078	0.002
6-month postoperative refraction (D)	-2.54±0.64	-2.41±0.83	-0.795	0.429
6-month postoperative refractive error (D)	0.88 [0.47, 1.62]	0.98 [0.43, 1.53]	0.488	0.625
6-month postoperative IOP (mmHg)	14.99±2.54	14.77±1.88	-0.469	0.64

Note: BCVA, Best Corrected Visual Acuity; UCVA, Uncorrected Visual Acuity; ACD, Anterior Chamber Depth; IOL, Intraocular Lens; MTF, Modulation Transfer Function; ECC, Endothelial Cell Count.

thickness (P=0.747), sex (P=0.454), affected side (P=0.153), diabetes history (P=0.904), smoking history (P=0.832), or alcohol consumption history (P=0.871).

At 6-month postoperatively, no significant between-group differences were observed in visual acuity outcomes, including BCVA (P=0.955), UCVA (P=0.326), ECD (P=0.225), refraction (P=0.379), refractive error (P=0.136), or IOP (P=0.889).

However, significant between-group differences were observed in several ocular and optical parameters. Specifically, ACD (P=0.049) was greater, while IOL vertical tilt (P=0.016), IOL horizontal tilt (P<0.001), and IOL decentration (P<0.001) were significantly lower in the experimental group compared with the control group. In addition, visual quality parameters, including MTF (P<0.001) and coma aberration (P<0.001), were significantly improved in the experimental group (**Table 9**).

Interaction effects of treatment protocol and age on 6-month postoperative outcomes

A significant interaction between treatment protocol and age was observed for ECD at 6 months (ECD_6m) (P=0.012), indicating that the effect of CTR implantation on ECD differed between age groups.

No significant interaction effects were found for other parameters, including IOL vertical tilt (IOL_VertTilt_6m) (P=0.968), IOL horizontal tilt (IOL_HorizTilt_6m) (P=0.370), and MTF (MTF_6m) (P=0.396), ACD (ACD_6m) (P=0.234), IOL decentration (P=0.191), or coma aberration (Coma_6m) (P=0.656) (**Figure 1** and **Table 10**).

Discussion

Cataract is a common eye disease in elderly populations, and the progressive aging of the population exacerbates its impact on visual quality [16]. Modern cataract surgery with intra-

Table 9. Comparison of baseline data and 6-month postoperative indicators in patients aged ≥60 years

Variable	Control Group (n=56)	Experimental Group (n=74)	t/Z/χ^2 Value	*P* Value
Age (years)	64.00 [62.00, 68.25]	65.00 [62.00, 68.75]	0.169	0.866
BMI (kg/m^2)	23.68±1.66	23.29±1.77	-1.266	0.208
White-to-white distance (mm)	12.33±0.88	12.30±0.95	-0.216	0.83
Axial length (mm)	30.20±2.26	30.24±2.09	0.092	0.927
Lens thickness (mm)	3.87 [3.63, 4.20]	3.88 [3.66, 4.23]	0.322	0.747
Gender (M/F)	26/26	32/42	0.561	0.454
Affected side (OD/OS)	32/20	36/38	2.042	0.153
Hypertension history (Y/N)	11/41	28/46	3.978	0.046
Diabetes history (Y/N)	11/41	15/59	0.015	0.904
Smoking history (Y/N)	27/25	37/37	0.045	0.832
Alcohol consumption history (Y/N)	9/43	12/62	0.026	0.871
6-month postoperative ACD	4.72±0.38	4.86±0.35	1.988	0.049
6-month postoperative BCVA	0.28 [0.12, 0.49]	0.27 [0.15, 0.47]	0.057	0.955
6-month postoperative IOL vertical tilt (°)	4.94 [4.57, 5.15]	4.58 [4.29, 5.04]	2.406	0.016
6-month postoperative IOL decentration (mm)	0.59±0.11	0.49±0.08	-5.738	<0.001
6-month postoperative IOL horizontal tilt (°)	4.92±0.83	4.32±0.73	-4.279	<0.001
6-month postoperative UCVA	0.67±0.03	0.67±0.04	-0.986	0.326
6-month postoperative MTF	0.66±0.12	0.74±0.11	4.092	<0.001
6-month postoperative coma aberration (μm)	0.67±0.13	0.55±0.20	-3.683	<0.001
6-month postoperative ECC (cells/mm^2)	2028.88±96.96	2009.77±78.56	-1.22	0.225
6-month postoperative refraction (D)	-2.44±0.81	-2.32±0.65	-0.883	0.379
6-month postoperative refractive error (D)	0.90 [0.47, 1.31]	1.12 [0.55, 1.82]	1.492	0.136
6-month postoperative IOP (mmHg)	15.22±2.51	15.27±1.89	0.14	0.889

Note: BCVA, Best Corrected Visual Acuity; UCVA, Uncorrected Visual Acuity; ACD, Anterior Chamber Depth; IOL, Intraocular Lens; MTF, Modulation Transfer Function; ECC, Endothelial Cell Count.

ocular lens (IOL) implantation can effectively restore vision. However, postoperative IOL decentration and tilt remain critical factors affecting visual quality, leading to refractive errors and compromised visual outcomes, especially in highly myopic patients with elongated axial lengths [17]. CTR is an auxiliary device designed to stabilize the capsular bag, thereby reducing IOL decentration and tilt and potentially improving postoperative visual quality.

Our findings demonstrate that CTR confers multiple advantages in this population. CTR significantly improved IOL positional stability: at 3 and 6 months post-operatively, the experimental group exhibited significantly lower IOL decentration, horizontal tilt, and vertical tilt compared to the control group. These results align with previous studies, which reported that CTR implantation in eyes with axial length ≥30 mm significantly reduces decentration and tilt of C-loop IOLs and improves IOL positional stability [18]. Likewise, CTR has been shown to improve rotational stability of multifocal toric IOLs in highly myopic eyes [12]. The benefits of CTR is especially pronounced in highly myopic eyes with elongated axial lengths (>26.5 mm), where the capsular bag is often fragile. CTR preserves the circular contour and inherent tension of the capsular bag through uniform expansion, providing a more stable and centered support for the IOL. This counteracts capsular fibrosis contraction and IOL displacement, thus laying the foundation for improved postoperative visual quality.

Consistent with these mechanical advantages, objective assessments of optical performance showed significant improvement in the CTR group. Analysis of MTF and coma aberration at 6 months postoperatively showed that the experimental group demonstrated significantly higher MTF values and significantly lower coma aberration than the control group, indicating superior objective optical quality. Park et al. [19] reported that CTR-implanted eyes had significantly higher internal MTF values at 20, 25

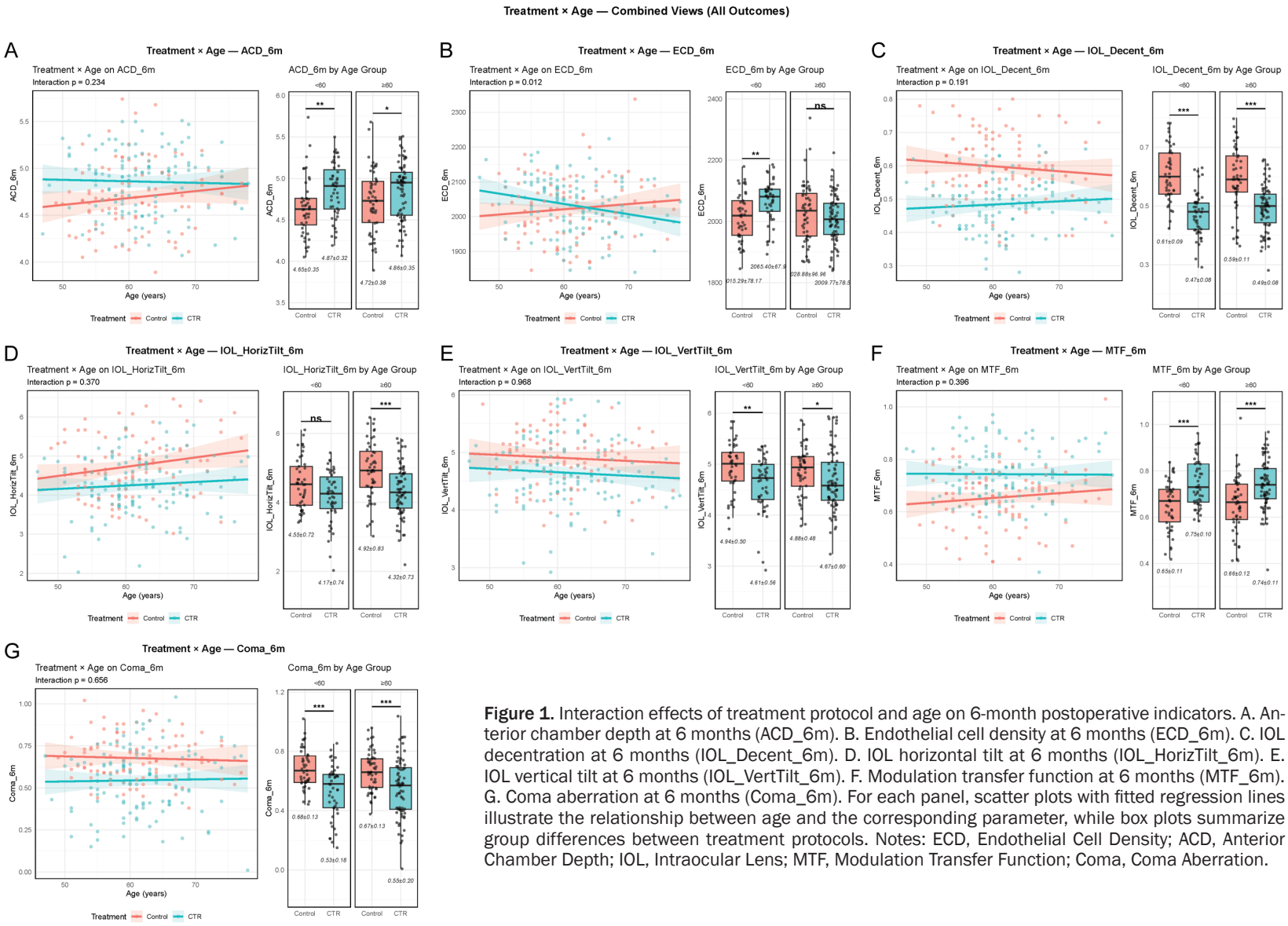

Figure 1. Interaction effects of treatment protocol and age on 6-month postoperative indicators. A. Anterior chamber depth at 6 months (ACD_6m). B. Endothelial cell density at 6 months (ECD_6m). C. IOL decentration at 6 months (IOL_Decent_6m). D. IOL horizontal tilt at 6 months (IOL_HorizTilt_6m). E. IOL vertical tilt at 6 months (IOL_VertTilt_6m). F. Modulation transfer function at 6 months (MTF_6m). G. Coma aberration at 6 months (Coma_6m). For each panel, scatter plots with fitted regression lines illustrate the relationship between age and the corresponding parameter, while box plots summarize group differences between treatment protocols. Notes: ECD, Endothelial Cell Density; ACD, Anterior Chamber Depth; IOL, Intraocular Lens; MTF, Modulation Transfer Function; Coma, Coma Aberration.

Table 10. Effects of treatment protocol - age interaction on 6-month postoperative indicators

Outcome	estimate	std. error	statistic	*p*.value	conf.low	conf.high
ECD_6m	-4.471	1.760	-2.540	0.012	-7.940	-1.001
IOL_Decent_6m	0.002	0.002	1.310	0.191	-0.001	0.006
ACD_6m	-0.009	0.007	-1.193	0.234	-0.024	0.006
IOL_HorizTilt_6m	-0.015	0.016	-0.898	0.370	-0.047	0.017
MTF_6m	-0.002	0.002	-0.851	0.396	-0.007	0.003
Coma_6m	0.002	0.004	0.446	0.656	-0.005	0.009
IOL_VertTilt_6m	0.000	0.012	-0.040	0.968	-0.023	0.022

Note: ECD, Endothelial Cell Density; ACD, Anterior Chamber Depth; IOL, Intraocular Lens; MTF, Modulation Transfer Function; Coma, Coma Aberration.

and 30 cycles/degree compared to controls, indicating superior optical system performance and clearer vision. In addition to objective optical improvements, the subjective visual experience of patients was significantly improved after CTR co-implantation. One month after surgery, DLI and QVI were significantly higher in the experimental group compared with the control group. IOL decentration and tilt are reflected by glare and visual blur. By stabilizing the IOL and reducing optical aberrations, CTR improved overall visual comfort and patient satisfaction, thereby positively impacting daily life activities. Consistently, Kwon et al. reported that eyes receiving CTR exhibited significantly lower mean absolute refractive errors at 1, 2, and 6 months postoperatively, indicating enhanced refractive accuracy [20].

Regarding ocular indicators, the experimental group showed significantly greater ACD than the control group at 1, 3, and 6 months after surgery. This may be attributable to the CTR's expansion of the capsular bag and its maintenance of the IOL in a more posterior position, consistent with literature reporting a hyperopic shift associated with posteriorly positioned IOLs following CTR implantation [19]. Maintaining a normal ACD is critical for stable intraocular environment and may reduce the risk of postoperative complications. IOP exhibited no significant difference between groups at any time point, pre- or postoperatively, confirming that CTR implantation is a safe procedure and without adverse effects on IOP.

Importantly, although the CTR group required more attempts to achieve optimal IOL stability, no significant differences were observed in BCVA, UCVA, or refractive error between the two groups at any observed time point. This discrepancy can be explained by the distinction between visual "quantity" and visual "quality". Both BCVA and UCVA are measures of visual quantity, which can be corrected with spectacles even in the presence of minor IOL decentration or tilt, whereas CTR enhances optical quality primarily by reducing higher-order aberrations and improving overall visual experience. The refractive error measured in this study mainly reflects lower-order aberrations (e.g., sphere and cylinder), whereas CTR exerts its effect mainly on higher-order aberrations, which do not substantially alter the overall refractive status but improve subjective visual quality. Hu et al. [21] showed that in high myopic eyes, prophylactic CTR implantation reduced capsular contraction and opacification without significantly affecting IOL stability or visual outcomes. Additionally, Zhao et al. [22] reported that postoperative IOL position in highly myopic cataract eyes is relatively stable. Collectively, these findings underscore that the clinical significance of CTR lies not in altering conventional visual acuity or refractive measures, but in optimizing visual quality.

In the interaction analysis of treatment protocol and age, age-related factors may have some effect on the CTR. The postoperative ECD at 6 months post-surgery showed a significant age-by-treatment interaction, whereas IOL horizontal tilt exhibited a trend without reaching statistical significance. This indicates that the effect of CTR on corneal endothelial cells may differ between younger (<60 years) and older (≥60 years) patients. However, no significant age-by-treatment interaction was detected for IOL horizontal tilt, MTF, or coma aberration. Although subgroup analyses showed significant treatment effects within both age groups for most indicators, age-specific efficacy should be

interpreted cautiously. Such differences may reflect physiologic variation, such as differences in capsular bag elasticity, substrate fibrosis severity, healing responses, and inflammatory tolerance. For instance, the capsular bag of younger patients tends to be more elastic, allowing more effective CTR expansion, whereas older patients may have more brittle or fibrotic capsular tissue, potentially compromising CTR efficacy. Consistently, Vokrojová et al. [23] found that eyes with axial length ≥24 mm showed a higher proportion of IOL axes matching the planned axis when CTR was used. Future investigations are needed to elucidate the biologic basis of these age-related differences.

It is noteworthy that in eyes without zonular instability, CTR co-implantation may paradoxically increase IOL decentration, likely due to interference between the CTR and IOL haptics. This underscores the importance of careful patient selection and precise assessment of CTR indications to avoid unnecessary or potentially counterproductive use. Supporting these findings, the literature suggests that in cases with suspected zonular weakness, CTR implantation can significantly reduce toric IOL decentration and axis deviation, thereby optimizing postoperative visual function [24, 25]. Proper evaluation of zonular status and capsular bag characteristics is essential to maximize the benefits of CTR implantation.

The study has several strengths. First, is the retrospective comparative design with clearly defined inclusion and exclusion criteria which offered a reliable framework for evaluating CTR efficacy. Second, visual quality was comprehensively assessed using both objective indicators-including IOL decentration, tilt, MTF, and coma aberration-and subjective indicators such as DLI and QVI. Third, the study focused on a high-risk population of highly myopic cataract patients, providing clinically relevant guidance for this population. Finally, the 6-month follow-up period allowed evaluation of the medium-term effects and stability of CTR on IOL positioning and visual outcomes.

Inevitably, this study had several limitations. As a retrospective, single-center study, it is susceptible to selection bias and confounding factors, which may limit the generalizability of the findings. The study population was limited to highly myopic patients, not necessarily applicable to other populations. Although the 6-month follow-up period provides meaningful insight into medium-term outcomes, longer-term evaluation is still needed to evaluate IOL stability and complications such as posterior capsule opacification. Specific IOL types were not clearly specified, and subgroup sample sizes in interaction analyses were relatively small, potentially limiting statistical power. Additionally, although DLI and QVI were initially recorded at 1, 3, and 6 months postoperatively, substantial missing data at the 3- and 6-month timepoints precluded longitudinal subjective analysis, reflecting the absence of routine long-term subjective visual quality assessment at our institution. Future prospective studies should incorporate standardized, long-term subjective assessments to enable a more comprehensive evaluation of patient-perceived visual quality.

For special populations, such as patients with Marfan syndrome or lens dislocation, previous studies [26, 27] have demonstrated that CTR combined with capsular hooks or modified CTR implantation is safe and effective. Similarly, early lens aspiration combined with CTR and posterior chamber IOL implantation in microspherophakia can prevent lens-induced complications [28], and CTR implantation after toric IOL implantation can provide better rotational stability and astigmatic correction [29]. Furthermore, as a retrospective study, direct measurement of capsular tension and posterior capsule contraction was not performed, and quantitative correlations between IOL positional indicators and optical quality outcomes were not pre-specified. Future prospective studies incorporating biomechanical capsular measurements and mediation analyses are warranted to elucidate the mechanistic pathway linking CTR implantation to visual quality improvement. In addition, the study period spanning from November 2022 to December 2024 with a maximum follow-up of 6 months precludes assessment of long-term complications such as posterior capsule opacification, and no cost-effectiveness analysis was performed due to the absence of economic data collection in the original protocol. These represent important directions for future investigation.

The findings of this study strongly support the application of CTR in highly myopic cataract surgery. Our results suggest that both surgeons and ophthalmologists should focus not only on standard visual acuity outcomes but also prioritize IOL positional stability as a key determinant of postoperative visual quality. Routine CTR implantation may optimize surgical protocols in high-risk patients. Nevertheless, treatment strategies should remain individualized, taking into account patient age, ocular parameters, and specific surgical considerations. Future research should carry out large-scale, multicenter, prospective randomized controlled trials with extended follow-up to evaluate the effects of different CTR and IOL designs in specific clinical scenarios. Incorporation of long-term complication monitoring, including posterior capsule opacification and formal cost-effectiveness analyses, will enable more precise clinical decision-making and guide individualized CTR implantation protocols.

Conclusion

This study demonstrated that CTR significantly improves postoperative visual quality in patients undergoing highly myopic cataract surgery. The primary benefits include the reduction of IOL decentration and tilt, which in turn improves objective optical performance (higher MTF and lower coma aberration) and subjective visual outcomes (higher DLI and QVI scores). Additionally, CTR positively influences ACD without affecting IOP. In addition, patient age modifies the effect of CTR on endothelial cell counts, highlighting the need for individualized treatment strategies. Overall, CTR represents a valuable adjunct in cataract surgery for high-risk eyes, offering both objective and subjective improvements in visual quality.

Disclosure of conflict of interest

None.

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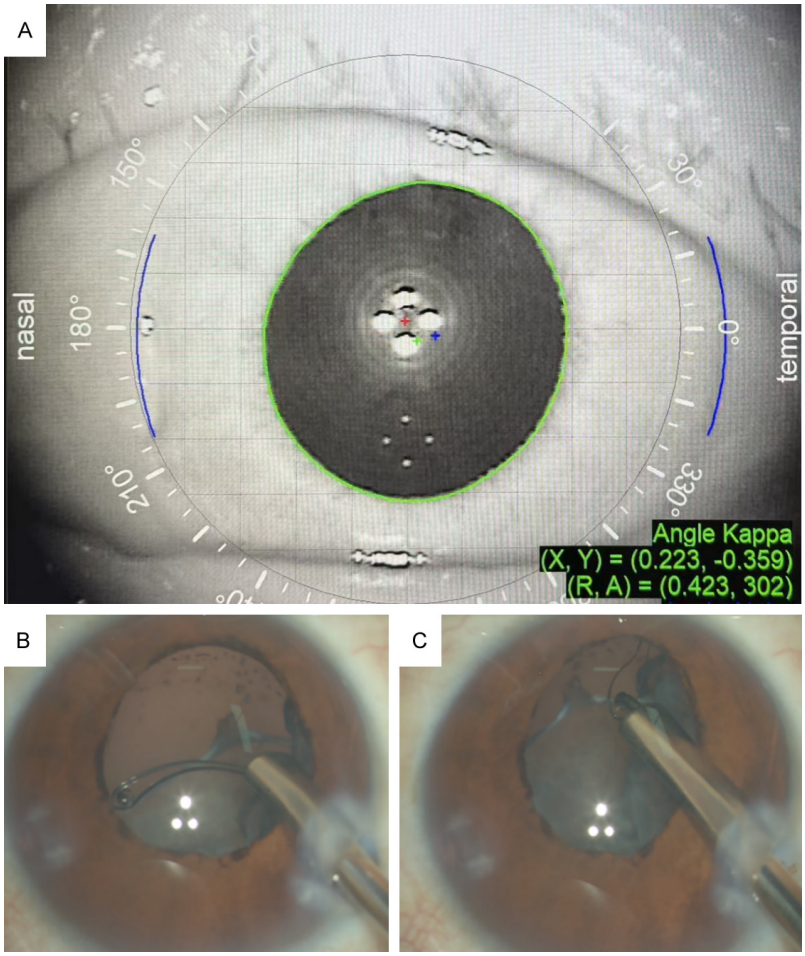

Figure S1. Representative images showing IOL decentration measurement and CTR implantation procedure. A. Measurement of IOL decentration using the iTrace visual function analyzer, showing angle kappa coordinates (X, Y) = (0.223, -0.359) and polar coordinates (R, A) = (0.423, 302). B. Intraoperative image showing the initial insertion of the CTR into the capsular bag. C. Intraoperative image showing successful CTR implantation, with the ring fully positioned within the capsular bag. Notes: IOL, Intraocular Lens; CTR, capsular tension ring.

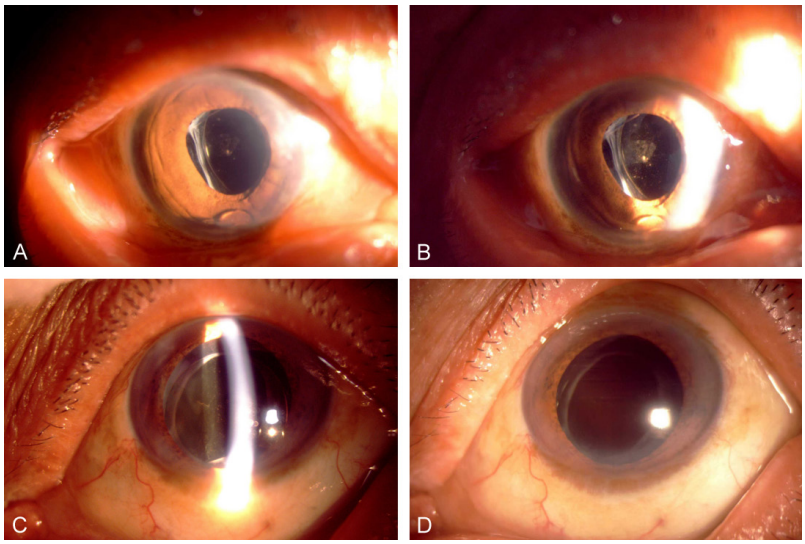

Figure S2. Representative slit-lamp images showing IOL position at 6 months postoperatively. A, B. Representative anterior segment slit-lamp photographs from the control group (IOL implantation only) at 6 months postoperatively. Mild asymmetry of the IOL optic edge is observed, suggesting slight IOL decentration within the capsular bag. C, D. Representative anterior segment slit-lamp photographs from the experimental group (CTR+IOL implantation) at 6 months postoperatively. The IOL appears well-centered with stable positioning within the capsular bag following CTR implantation. Notes: IOL, Intraocular Lens; CTR, Capsular Tension Ring.