

Comparative Study of ICL V4c Decentration in Vertical vs Horizontal Implantation: Association with Angle Alpha and Validation of Equivalent Visual Quality

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Purpose: To compare the decentration of the Implantable Collamer Lens (ICL) V4c and its impact on visual quality between vertical and horizontal implantation techniques.

Methods: 50 patients (80 eyes) were assigned to horizontal (40 eyes) or vertical (40 eyes) implantation groups. Preoperative and 6-month postoperative evaluations included uncorrected (UDVA) and corrected distance visual acuity (CDVA), refractive status, corneal topography, and wavefront aberration analysis. Decentration was measured using the OPD-Scan III aberrometer, compared between implantation methods, and analyzed for associations with preoperative angles α and κ .

Results: At 6 months, 100% of horizontal and 97.5% of vertical implantation eyes achieved UDVA $\geq 20/20$, with all eyes maintaining or improving CDVA. Mean decentration was similar between groups (horizontal: 0.42 ± 0.18 mm; vertical: 0.42 ± 0.19 mm; $p = 0.915$), with temporal displacement predominating. Angle α significantly correlated with decentration in both groups ($p = 0.016$; $p = 0.017$), while angle κ showed no association ($p > 0.05$). The change of higher-order aberrations did not differ between groups ($p > 0.05$), and decentration magnitude did not clinically affect optical quality ($p > 0.05$ for all aberration parameters).

Conclusion: Vertical and horizontal ICL V4c implantation demonstrated comparable centration and visual outcomes. Decentration was significantly associated with preoperative angle α , underscoring the clinical importance of angle α assessment for optimal ICL positioning.

Keywords: ICL V4c, decentration, vertical implantation, visual outcomes, angle alpha, wavefront aberrations

Introduction

The global burden of visual impairment persists, largely due to uncorrected refractive errors, while myopia prevalence shows a consistent upward trend.¹ In this context, the Implantable Collamer Lens (ICL) V4c, an advanced phakic intraocular lens, has emerged as a key solution for myopia correction. Although extensive evidence supports the safety and efficacy of ICL procedures,²⁻⁶ greater emphasis is now placed on attaining highly accurate refractive corrections and superior visual acuity after surgery. The glare, halos, and starburst phenomena that occur during lens decentration can significantly affect patient visual outcomes.⁷⁻¹⁰

Optimal positioning of an ICL requires alignment between the center of the optical zone and the visual axis. However, owing to the fixation of the ICL in the ciliary sulcus, anatomical variations in the sulcal structure and haptic positioning



can prevent ideal alignment.^{11,12} ICL optical zone decentration can compromise visual quality;¹³ however, few studies have investigated the factors influencing this decentration.

With an enhanced understanding of the ciliary sulcus anatomy, vertical implantation has gained increasing acceptance as a management strategy for vault and rotational stability. Prior research has demonstrated that vertical implantation achieves superior vault and rotational stability compared with horizontal implantation, establishing it as a safe and effective approach for myopia correction.^{14–17} However, previous studies examining ICL positioning and decentration have primarily focused on horizontal implantation, with limited investigations into vertical implantation outcomes, and without comparative assessment of visual quality between the two approaches. Here, we aimed to compare ICL decentration and visual outcomes between vertical and horizontal implantation techniques, while also identifying other contributing and associated factors.

Methods

Patient Cohort

This retrospective analysis evaluated 50 patients (80 eyes) who received ICL V4c implantation at the Eye and ENT Hospital of Fudan University, Shanghai, China from May to August 2024. Eligible eyes met the following criteria: anterior chamber depth (ACD) ≥ 2.8 mm and endothelial cell density ≥ 2500 cells/mm². Exclusion criteria comprised perioperative or postoperative complications (eg, elevated intraocular pressure, significant inflammation, or lens opacity). The study adhered to the tenets of the Declaration of Helsinki and received institutional ethics approval (Ethics Committee of the Eye and ENT Hospital, Fudan University). Written informed consent was obtained from all the patients.

Surgical Method

All ICL implantations were performed by a single experienced surgeon (XZ). The ICL size was based on the white-to-white (WTW) distance and ACD (Pentacam, Oculus Optikgeräte, Wetzlar, Germany). The choice of ICL resizing and implantation orientation followed a standardized protocol based on preoperative anatomical measurements, as previously reported.¹⁸ To establish the ICL diopter power, we selected the myopic and astigmatic powers that provided a refractive outcome closest to zero diopters. All implanted lenses in this study were spherical ICL V4c models; no toric ICLs were used.

Preoperatively, after topical anesthesia (0.4% oxybuprocaine), all patients were positioned upright with their gaze fixed on a far target. Cyclotorsion adjustment markers were applied at the 3-, 9-, and 12-o'clock positions using a slit beam to account for potential cyclotorsion during the procedure.

Dilating eye drops and topical anesthesia were administered before surgery. A 3.0-mm clear corneal incision was created temporally. The ICL V4c was then inserted along the predetermined axis (horizontal or vertical orientation) anterior to the native crystalline lens. A standardized ICL surgical protocol was followed, as previously reported.¹⁹ Postoperatively, topical antibiotics (0.5% levofloxacin; Santen) and steroids (1.0% prednisolone acetate, Pred Forte; Allergan, Irvine, CA, USA) were administered four times daily for 7 days. Additionally, a topical nonsteroidal anti-inflammatory drug (pranoprofen, Senju, Osaka, Japan) was applied four times daily for 14 days.

Preoperative and Postoperative Assessment

A complete ophthalmic evaluation was performed both before surgery and at the 6-month postoperative follow-up, encompassing visual acuity assessments including uncorrected (UDVA) and corrected distance visual acuity (CDVA) measured with Snellen charts, along with comprehensive refractive evaluation through both manifest and cycloplegic techniques. The examination protocol further incorporated anterior and posterior segment analysis via slit lamp biomicroscopy and funduscopy, intraocular pressure measurement using non-contact tonometry, and detailed corneal assessment through topography and pachymetry (Pentacam, Oculus, Germany). Additional biometric parameters included WTW distance and axial length measurements (IOL Master, Carl Zeiss, Germany), anterior chamber depth evaluation, and corneal endothelial cell density quantification (SP-3000P specular microscope, Topcon, Japan). Advanced imaging modalities consisted of optical coherence tomography (Optovue, USA) and ultrasound biomicroscopy (Quantel Medical, France) for comprehensive ocular structure analysis.

Decentration and Aberration Measurements

Higher-order aberrations (HOAs) were measured preoperatively and 6 months postoperatively using an OPD-Scan III aberrometer (Nidek Co., Ltd., Gamagori, Japan) for a central 4-mm analytical zone with higher-order aberrations up to the sixth order of the Zernike polynomials. The root mean square value was used to quantify whole-eye HOAs. ICL decentration was quantitatively assessed using the OPD-Scan III aberrometer under standardized mesopic lighting conditions (3 cd/m^2) to minimize pupil diameter effects on lens positioning. During measurement, patients maintained fixation on the device's point light source, with the visual axis defined as the line connecting this target to the fovea. The system's retrobulbar illumination analysis mode simultaneously identified both the visual axis and the ICL V4c's anatomical center ($360 \mu\text{m}$ central hole). Decentration was calculated as the linear displacement between these two reference points, consistent with established methodologies described in prior studies.^{20,21}

Statistical Analysis

Statistical analysis was conducted with IBM SPSS Statistics (v20.0, SPSS Inc., Chicago, IL). Continuous variables were expressed as mean \pm standard deviation or median with interquartile range (IQR) following verification of normal distribution using the Shapiro–Wilk test. Pearson or Spearman was employed based on the distribution characteristics of the data. Polar coordinate plots illustrating the overall distribution of ICL postoperative eccentricity were generated using R (version 4.4.3, R Foundation for Statistical Computing, Vienna, Austria). Intergroup comparisons were performed with independent *t*-tests or Mann–Whitney *U*-Test according to data distribution, while variable relationships were assessed through simple linear regression. A *p*-value threshold of 0.05 was established for determining statistical significance.

Results

Baseline Characteristics

The study cohort comprised 50 participants (80 eyes) receiving ICL implantation, with the horizontal implantation subgroup consisting of 12 male (48.0%) and 13 female (52.0%) patients. These subjects demonstrated a mean age of 21.0 ± 2.3 years (range 18 to 26 years) and presented with moderate to high myopia, as evidenced by a mean spherical refraction of $-6.87 \pm 2.08 \text{ D}$ (range -11.50 to -3.50 D). The median and IQR of preoperative astigmatic refraction was -1.00 (0.75) D, and mean preoperative refractive spherical equivalent was $-7.36 \pm 2.06 \text{ D}$ (range: -12.00 to -4.25 D).

The vertical implantation cohort comprised 25 patients (44.0% male, $n = 11$; 56.0% female, $n = 14$) with comparable demographic characteristics, showing a mean age of 21.2 ± 2.4 years (age range: 18 to 26 years). The mean preoperative refractive sphere was $-6.67 \pm 1.87 \text{ D}$ (range: -10.50 to -3.00 D), median and IQR of preoperative astigmatic refraction was -1.00 (0.25) D, and mean refractive spherical equivalent was $-7.17 \pm 1.85 \text{ D}$ (range: -11.13 to -3.50 D).

Table 1 presents the baseline demographic and clinical characteristics of the study participants, all preoperative parameters showed no statistically significant differences between the two groups ($P > 0.05$). All implantation procedures were completed without intraoperative complications, and the postoperative course remained uneventful, with no occurrence of sight-threatening adverse events throughout the observation period.

Postoperative Visual and Refractive Outcomes

Six months postoperatively, visual acuity outcomes demonstrated excellent results across both surgical groups. In the horizontal cohort, all operated eyes (40/40, 100%) attained UDVA of 20/20 or superior, while the vertical group showed nearly equivalent success (39/40 eyes, 97.5%). Notably, CDVA was maintained or enhanced in every case (40/40, 100%) for both implantation approaches, as illustrated in Figure 1A and B. Regarding predictability, the regression equation for achieved versus attempted spherical equivalent (SE) correction was

$$y = 1.0060x + 0.0193$$

($R^2 = 0.9737$) in the horizontal group and

$$y = 0.9964x - 0.0354$$

Table 1 Preoperative Patient Demographics and Clinical Characteristics

Parameters	Vertical Group	Horizontal Group	P value
Patients (eyes, n)	40 (25)	40 (25)	–
CDVA (D)	1.00 (0.00)	1.00 (0.00)	0.155 ^b
DS (D)	−6.67±1.87	−6.87±2.08	0.652 ^a
DC (D)	−1.00 (0.25)	−1.00 (0.75)	0.494 ^b
SE (D)	−7.17±1.85	−7.36±2.06	0.660 ^a
AL (mm)	26.49±1.18	26.60±1.47	0.751 ^a
ACD (mm)	3.62±0.21	3.60±0.26	0.791 ^a
Km (D)	43.58±1.64	43.72±1.63	0.703 ^a
WTW (mm)	11.99±0.50	11.86±0.42	0.199 ^a
Angle alpha (mm)	0.27±0.12	0.29±0.16	0.599 ^a
Angle kappa (mm)	0.22±0.12	0.26±0.15	0.159 ^a
HOA (μm)	0.14 (0.09)	0.15 (0.09)	0.988 ^b
SA (μm)	0.02 (0.03)	0.02 (0.02)	0.301 ^b
CA (μm)	0.04 (0.04)	0.05 (0.04)	0.881 ^b
Tri (μm)	0.10 (0.08)	0.09 (0.11)	0.427 ^b
VT (μm)	−0.03±0.08	−0.03±0.09	0.912 ^a
VC (μm)	−0.01±0.10	0.00±0.05	0.908 ^a
HC (μm)	0.00±0.06	−0.01±0.05	0.593 ^a
OT (μm)	−0.01 (0.13)	−0.02 (0.08)	0.985 ^b

Note: data are shown as mean ± standard deviation or median with interquartile range (IQR) according to their distribution. ^a Independent t-tests. ^b Mann–Whitney U-Test.

Abbreviations: ACD, anterior chamber depth; AL, axis length; CA, coma aberration; CDVA, corrected distance visual acuity; DC, Diopter Cylinder; DS, diopter sphere; HC, horizontal coma; HOA, Higher Order Aberration; Km, keratometry mean; OT, oblique trefoil; SA, spherical aberration; SE, spherical equivalent; Tri, trefoil; VC, vertical coma; VT, vertical trefoil; WTW, white-to-white.

($R^2 = 0.9464$) in the vertical group (Figure 1C). At 6 months postoperatively for spherical equivalent accuracy, 87.5% of horizontally implanted eyes (35/40) and 85.0% of vertically implanted eyes (34/40) achieved results within ± 0.50 D of the target, with all horizontal cases (100%) and 97.5% of vertical cases (39/40) falling within ± 1.00 D (Figure 1D). Astigmatic correction presented 80% (32/40) and 75% (30/40) of eyes in the horizontal and vertical groups respectively attaining ≤ 0.50 D residual cylinder, while all eyes (100%) in both groups maintained ≤ 1.00 D (Figure 1E). Refractive stability was exceptional, with merely 2.5% of cases (1/40 per group) exhibiting spherical equivalent variations > 0.5 D during follow-up (Figure 1F).

Postoperative Optical Zone Decentration

Quantitative analysis of ICL decentration revealed comparable results between surgical approaches, with mean total displacement measuring 0.42 ± 0.18 mm (range 0.11 to 0.91 mm) for horizontal implantation and 0.42 ± 0.19 mm (range 0.08 to 0.81 mm) for vertical implantation ($p = 0.915$). The decentration was vectorially decomposed. In the horizontal implantation group, the mean horizontal decentration was 0.06 ± 0.39 mm (range: -0.62 to 0.76 mm), and the mean vertical decentration was 0.10 ± 0.23 mm (range: -0.59 to 0.63 mm). In the vertical implantation group, the mean horizontal decentration was -0.02 ± 0.41 mm (range: -0.74 to 0.81 mm), and the mean vertical decentration was 0.00 ± 0.21 mm (range: -0.45 to 0.50 mm). No statistically significant differences were observed in either the horizontal or vertical vector components of decentration between the two groups ($P = 0.373$ and $P = 0.055$, respectively; Table 2). Spatial distribution analysis (Figure 2) identified a consistent temporal displacement pattern for the central aperture in both techniques. In both the vertical and horizontal implantation groups, 77.5% of eyes exhibited temporal ICL eccentricity. Specifically, in the vertical implantation group, 18 eyes (45.0%) were located in the inferotemporal quadrant, 13 eyes (32.5%) in the superotemporal quadrant, 5 eyes (12.5%) in the superonasal quadrant, and 4 eyes (10.0%) in the inferonasal quadrant. In the horizontal implantation group, 18 eyes (45.0%) were located in the superotemporal quadrant, 13 eyes (32.5%) in the inferotemporal

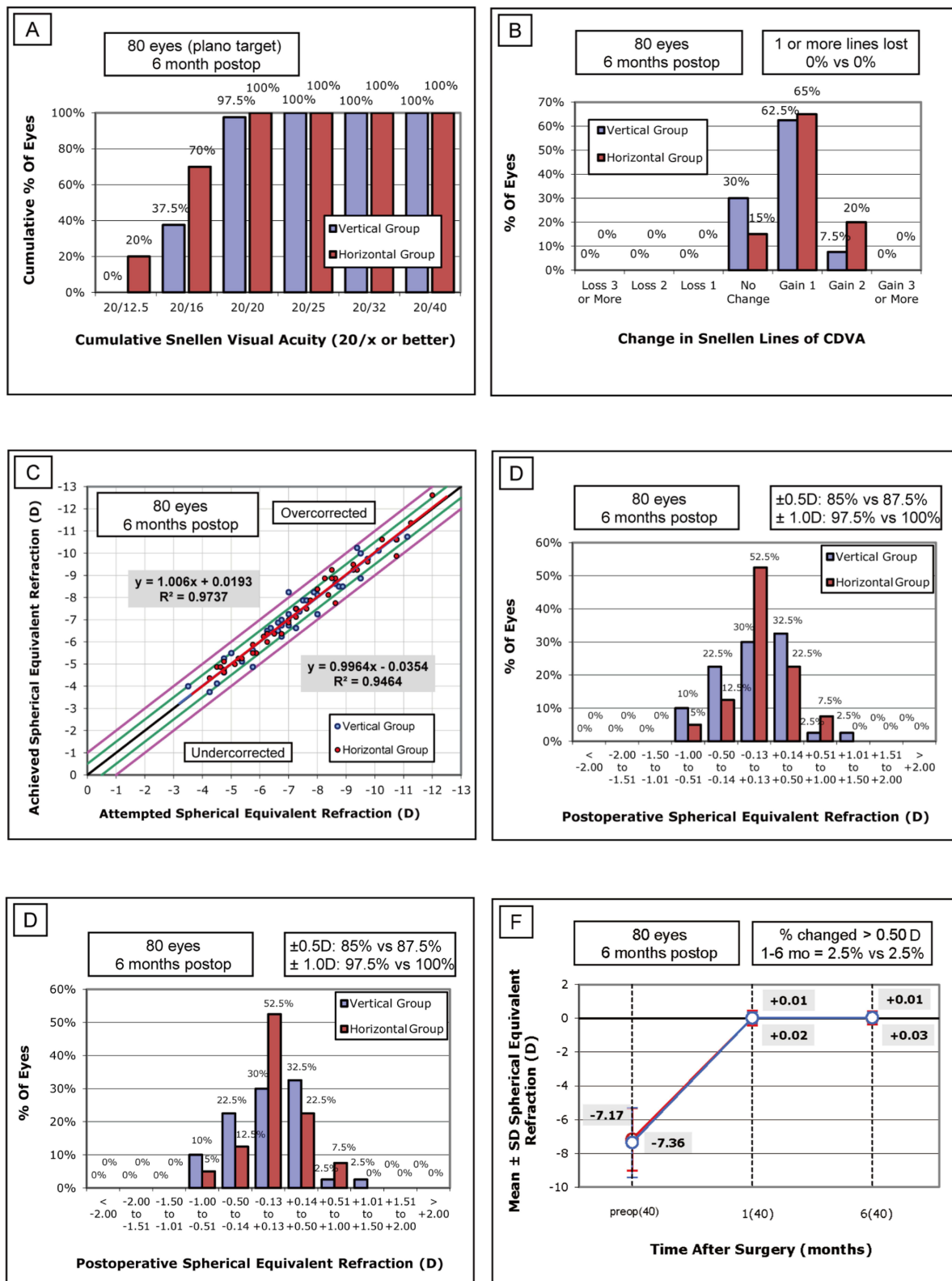


Figure 1 Visual outcomes at 6 months postoperatively. **(A)** Uncorrected Distance Visual Acuity (UDVA); **(B)** Change in Corrected Distance Visual Acuity (CDVA); **(C)** Spherical Equivalent Refraction attempted versus achieved; **(D)** Postoperative Spherical Equivalent Refraction accuracy; **(E)** Postoperative Refractive Astigmatism; **(F)** Stability of Spherical Equivalent Refraction over time.

Table 2 Comparison of Optical Zone Decentration Between Two Positioning Methods

Group	Horizontal Decentration (mm)	Vertical Decentration (mm)	Total Decentration (mm)
Vertical	-0.02±0.41 (-0.74, 0.81)	0.00±0.21 (-0.45, 0.50)	0.42±0.19 (0.08, 0.81)
Horizontal	0.06±0.39 (-0.62, 0.76)	0.10±0.23 (-0.59, 0.63)	0.42±0.18 (0.11, 0.91)
P value	0.373	0.055	0.915

quadrant, 5 eyes (12.5%) in the superonasal quadrant, and 4 eyes (10.0%) in the inferonasal quadrant. Regression analysis demonstrated a clinically relevant correlation between preoperative angle α and total decentration magnitude in both groups ($R^2 = 0.1404$, $p = 0.017$ for horizontal; $R^2 = 0.1424$, $p = 0.016$ for vertical), whereas no significant correlation was observed between angle κ and total decentration ($R^2 = 0.0507$, $p = 0.162$ for horizontal; $R^2 = 0.0037$, $p = 0.711$ for vertical). Furthermore, we decomposed angle α , angle κ , and total decentration into horizontal and vertical components to investigate their directional correlations. The analysis revealed that angles α and κ exhibited directionally consistent correlations with

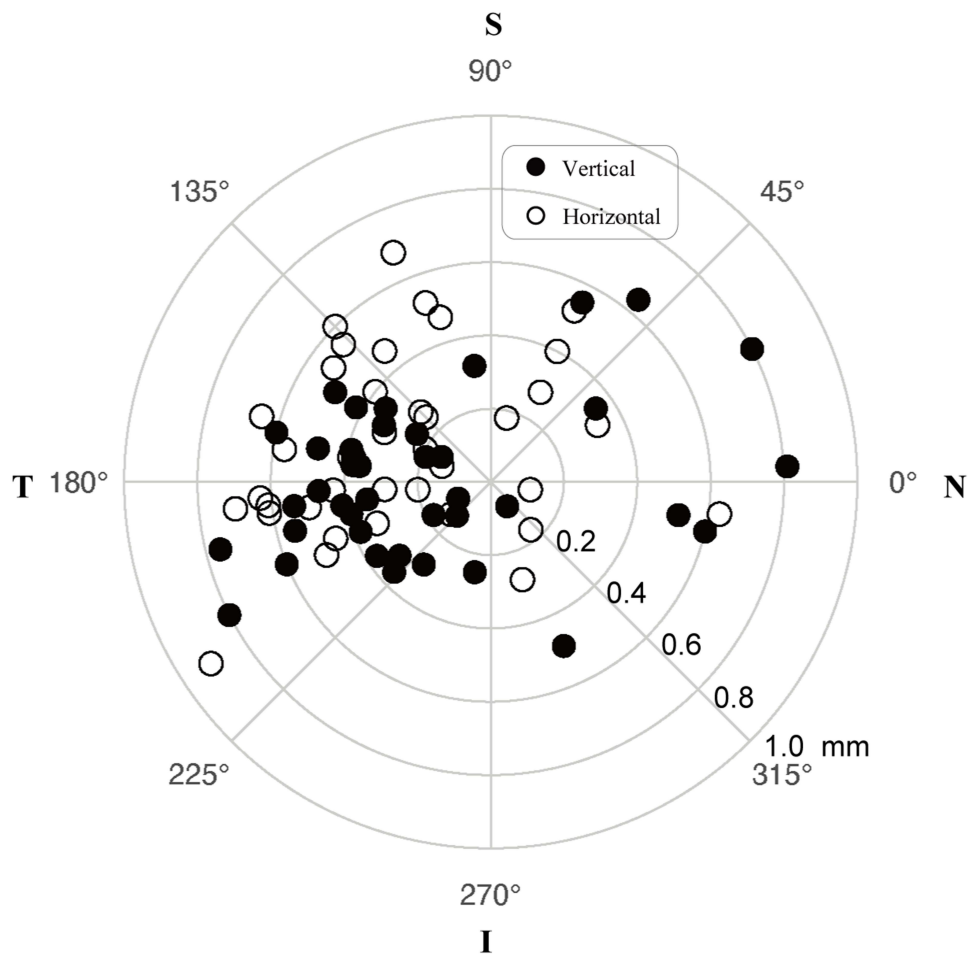


Figure 2 Distribution of Optical Zone Decentration. The polar plot illustrates the spatial distribution of the central hole position. **Note:** Decentration data from left eyes were mirrored to the corresponding positions in the right eye orientation. **Abbreviations:** I, inferior; N, nasal; S, superior; T, temporal.

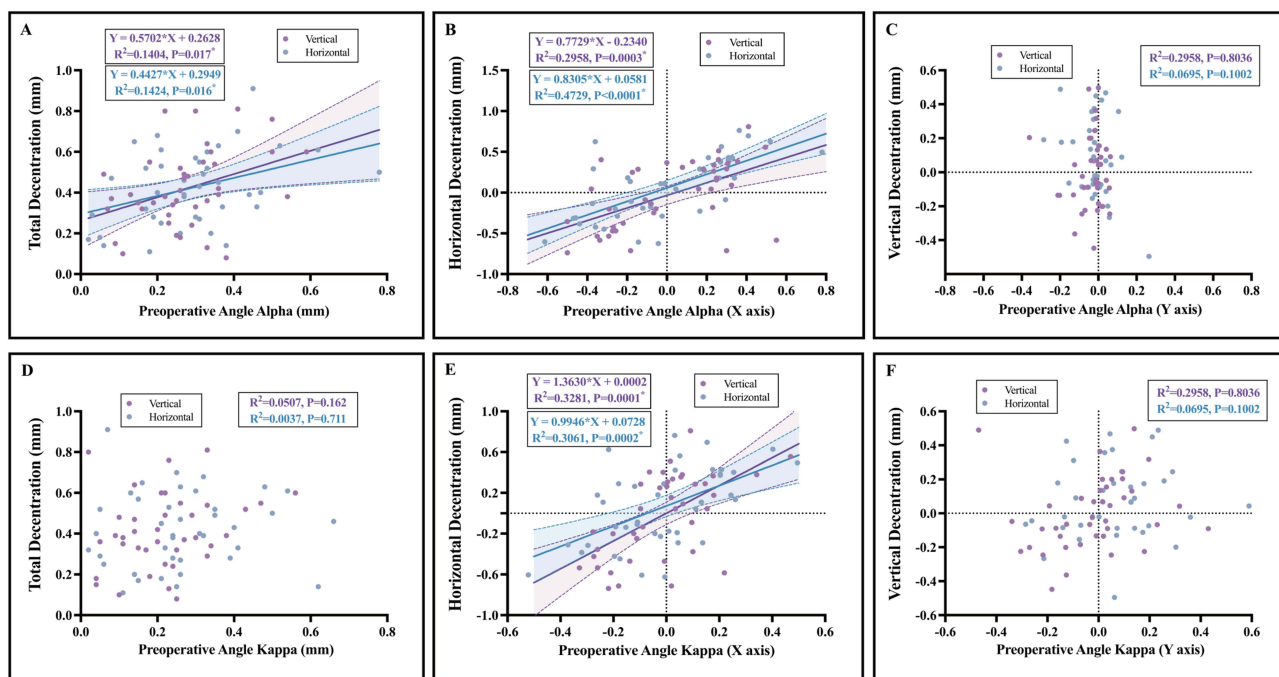


Figure 3 Correlation analysis between optical zone decentration and preoperative angles. (A) Angle α vs Total Decentration; (B) Angle α (X-axis component) vs Horizontal Decentration; (C) Angle α (Y-axis component) vs Vertical Decentration; (D) Angle κ vs Total Decentration; (E) Angle κ (X-axis component) vs Horizontal Decentration; (F) Angle κ (Y-axis component) vs Vertical Decentration. Blue lines represent the Horizontal Group; Purple lines represent the Vertical Group. Shaded areas indicate 95% confidence intervals.

decentration: in the horizontal direction, both horizontal components of angle α and angle κ showed positive correlations with horizontal decentration; in the vertical direction, neither the vertical components of angle α nor angle κ demonstrated a significant linear correlation with vertical decentration. Figure 3 illustrates the coefficient of determination (R^2), P-values, and linear regression equations (where correlations were significant) for the overall, horizontal, and vertical decomposition analyses.

Changes in Postoperative Wavefront Aberrations

Wavefront analysis at 6 months postoperatively demonstrated comparable optical quality between the two implantation techniques across all evaluated parameters (Table 3). No statistically significant differences were observed in the following parameters: total higher-order aberrations ($p=0.186$), spherical aberration ($p=0.200$), vertical coma ($p=0.707$), horizontal coma ($p=0.810$), vertical trefoil ($p=0.470$), and oblique trefoil ($p=0.884$). Changes in coma and trefoil from preoperative to postoperative states were calculated through vector decomposition analysis, which similarly revealed no significant differences in coma ($p=0.494$) or trefoil ($p=0.992$).

Correlation analysis demonstrated no significant association between total decentration magnitude and induced corneal aberrations in either group. The coefficient of determination (R^2) for all aberration-decentration relationships

Table 3 Comparison of Corneal Higher-Order Aberrations Changes Between Two Positioning Methods

Group	HOA	SA	CA	Tri	VT	VC	HC	OT
Vertical (μm)	0.02±0.08	0.00±0.03	0.00 (0.00)	0.01 (0.01)	0.00±0.12	-0.02 (0.05)	-0.00 (0.16)	0.03±0.12
Horizontal (μm)	0.05±0.11	0.01±0.02	0.00 (0.00)	0.01 (0.02)	-0.02±0.12	-0.02 (0.06)	-0.01 (0.05)	0.02±0.11
P value	0.186 ^a	0.200 ^a	0.494 ^b	0.992 ^b	0.470 ^a	0.707 ^b	0.810 ^b	0.884 ^a

Notes: ^aIndependent t-tests. ^b Mann-Whitney U-Test.

Abbreviations: HOA, Higher Order Aberration; SA, Spherical Aberration; CA, Coma Aberration; Tri, Trefoil; VT, Vertical Trefoil; VC, Vertical Coma; HC, Horizontal Coma; OT, Oblique Trefoil.

Table 4 Correlations Between Total Decentration and Corneal Aberration Changes in the Two Surgical Techniques

Parameters	Total Decentration			
	Vertical Group		Horizontal Group	
	r value	P value	r value	P value
HOA	0.050 ^a	0.758 ^a	0.009 ^a	0.954 ^a
SA	-0.084 ^a	0.608 ^a	0.192 ^a	0.236 ^a
CA	0.308 ^b	0.054 ^b	0.285 ^b	0.075 ^b
Tri	0.181 ^b	0.265 ^b	-0.020 ^b	0.904 ^b
VT	-0.046 ^a	0.777 ^a	0.188 ^a	0.245 ^a
VC	-0.230 ^b	0.154 ^b	0.138 ^b	0.396 ^b
HC	-0.105 ^b	0.517 ^b	-0.277 ^b	0.084 ^b
OT	0.021 ^a	0.895 ^a	0.035 ^a	0.829 ^a

Notes: ^aPearson correlation analysis; ^bSpearman correlation analysis.

Abbreviations: HOA, Higher Order Aberration; SA, Spherical Aberration; CA, Coma Aberration; Tri, Trefoil; VT, Vertical Trefoil; VC, Vertical Coma; HC, Horizontal Coma; OT, Oblique Trefoil.

was < 0.31 (range: 0.009 to 0.308), with p-values consistently > 0.05 (range: 0.054 to 0.954) (Table 4), confirming that optical performance remained unaffected by observed decentration magnitudes within both implantation approaches.

Discussion

Vertical ICL implantation has gained increasing acceptance as an advantageous technique for optimizing the vault height and rotational stability. Studies comparing horizontal versus vertical implantation have documented superior rotational stability with the vertical approach, reporting a mean rotation of 3.27° versus 1.74° in one series¹⁵ and 3.02° versus 1.11° in another investigation of toric ICLs.¹⁶ The potential for maintaining lower vault heights represents another benefit of vertical implantation,^{22–25} particularly given that the complications of excessive vault (endothelial cell loss and angle closure) tend to be irreversible, whereas those associated with low vault (particularly cataract formation) may be more manageable. Furthermore, the central hole design facilitates aqueous circulation and reduces the cataractogenic risk and angle closure. Our demonstration of equivalent decentration and optical performance of vertical versus horizontal implantation provides additional support for this emerging surgical approach.

In our study, analysis of the ICL V4c decentration based on the central hole position (KS-AquaPORT) revealed a predominantly temporal distribution of KS-AquaPORT in both the horizontal and vertical implantation groups. Previous studies evaluating ICL V4c decentration demonstrated similar temporal displacement of the KS-AquaPORT, particularly in the superotemporal quadrant, with mean decentration values of 0.34 mm relative to the pupillary axis and 0.47 mm relative to the visual axis.^{26,27} However, these earlier studies relied on slit-lamp photography combined with topographic coordinate conversion, which entails operator-dependent variability.

Our research team utilized the OPD-Scan III system for quantitative evaluation of KS-AquaPORT centration. Building on our previous findings documenting a mean decentration of 0.38 mm with temporal predominance relative to the visual axis,¹³ the current study systematically compares decentration characteristics between horizontal and vertical implantation approaches. The results demonstrate nearly identical mean decentration values (horizontal: 0.42 ± 0.18 mm; vertical: 0.42 ± 0.19 mm; p = 0.915), with no statistically significant intergroup differences. Regarding spatial distribution, the decentration was predominantly located temporally. In the vertical implantation group, 18 eyes (45.0%) were located in the inferotemporal quadrant and 13 eyes (32.5%) in the superotemporal quadrant. Correspondingly, in the horizontal implantation group, 18 eyes (45.0%) were located in the superotemporal quadrant and 13 eyes (32.5%) in the inferotemporal quadrant. This pattern occurs because vertical implantation rotates the central hole by 90 degrees around the visual axis compared to horizontal implantation, resulting in distinct spatial distribution patterns while maintaining identical radial distances. In other words, although

rotation affects the positional distribution of the central port, it does not alter the magnitude of decentration. Consequently, there was no statistically significant difference in decentration magnitude between vertical and horizontal implantation.

Notably, our analysis revealed significant correlations between the preoperative angle α and total decentration magnitude in both the horizontal and vertical implantation groups, whereas no such relationship was observed for angle κ . We postulate that this association stems from ICL fixation within the ciliary sulcus, with the KS-AquaPORT approximating the sulcus midpoint near the center of the crystalline lens. Because angle α represents the lens center displacement relative to the visual axis, its correlation with ICL decentration is mechanistically plausible.²⁸ To elaborate on this finding, it is crucial to distinguish between anatomical and functional centration. While the ICL V4c is designed to center anatomically within the ciliary sulcus, the visual axis does not always align with this anatomical center. Angle α represents the distance between the visual axis and the center of the crystalline lens, which the ICL approximates. Consequently, a large preoperative angle α inherently means that the visual axis is significantly offset from the ICL's anatomical center, even when the lens is perfectly positioned in the sulcus. Our OPD-Scan III measurements, which define decentration relative to the visual axis, therefore capture this "functional decentration". Our findings underscore the clinical importance of considering angle α as a predictor of postoperative functional centration. Conversely, angle κ , which describes the pupillary center offset from the visual axis, demonstrated no significant relationship with ICL decentration.²⁸ This study also found that the horizontal components of both angle α and angle κ showed positive correlations with ICL horizontal decentration, while no significant association was observed for vertical components (Figure 3). This phenomenon can be explained by the anatomical characteristics of the ciliary sulcus: The vertically oval-shaped sulcus, with its shorter horizontal diameter,²² limits the fixation of haptic, enabling the horizontal displacement of the lens center (angle α) and pupil center (angle κ) to synergistically influence ICL positioning through iris-ciliary body tension. In the vertical direction, the deeper sulcus with greater contact area, combined with gravity-assisted stabilization, creates a dual stabilization mechanism that significantly diminishes the regulatory effect of angular parameters. This finding aligns with clinically observed superior rotational stability in vertical implantation,^{14–16} suggesting that preoperative planning should specifically evaluate the synergistic effects of both angles in patients at high risk of horizontal decentration.

At six months post-surgery, all eyes in the horizontal group (40/40, 100%) achieved uncorrected distance visual acuity (UDVA) of 20/20 or better, while the vertical group demonstrated a nearly equivalent success rate (39/40 eyes, 97.5%). These findings are largely consistent with previous studies.^{14,16} Regarding aberrations, previous studies have documented increased coma aberrations with greater ICL V4c decentrations and significantly higher HOAs²⁹ and trefoils in cases of large versus small decentrations.³⁰ However, its clinical impact on visual performance appears to be minimal. Multiple studies have shown that KS-AquaPORT positioning does not significantly affect uncorrected distance visual acuity (UDVA), contrast sensitivity under mesopic and glare conditions, total corneal HOAs, or quality-of-life indices.^{26,27,30} Our findings are consistent with those of a recent study by Niu et al,³¹ which demonstrated no significant correlations between decentration parameters and postoperative HOAs. This may be attributed to two main factors: first, the spherical optical design of the ICL reduces sensitivity to decentration; second, in our cohort, the average decentration in both groups (0.42 ± 0.18 mm and 0.42 ± 0.19 mm, respectively) remained below 0.5 mm, which may not have reached the threshold to significantly influence higher-order aberrations (HOAs). This may explain the absence of notable aberrative consequences. The absence of intergroup differences in HOAs changes further supports the comparable optical performance of both horizontal and vertical implantation approaches.

Our study has several limitations. First, as a retrospective study, it may be subject to selection bias, this was mitigated by strictly adhering to a standardized preoperative anatomical protocol for grouping assignment, rather than subjective surgeon preference. Additionally, our relatively small sample size and the specific patient population included may limit the generalizability of our findings. Furthermore, lack of decentration data at the early postoperative stage (eg, 1 week) prevented longitudinal analysis of positional stability from the immediate postoperative period. Finally, although we analyzed follow-up data at 6 months postoperatively, further research is needed to determine the long-term visual outcomes and complication rates.

The study demonstrated comparable visual quality and similar decentration outcomes between vertical and horizontal ICL implantation techniques, providing theoretical support for the emerging vertical implantation approach. Furthermore, a significant correlation was observed between preoperative angle α and decentration in both groups, highlighting the importance of angle α measurement during preoperative evaluations.

Data Sharing Statement

The data that support the findings of this study are available from the corresponding author (Zhou X) upon reasonable request.

Ethics Approval and Consent to Participate

Approval for this clinical study was granted by the Ethics Committee of Fudan University's Eye and ENT Hospital (No. 2021018), with strict adherence to Declaration of Helsinki guidelines. Written informed consent was acquired from all participants after thorough explanation of the study's procedures and possible effects.

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Disclosure

The authors declare that they have no competing interests.

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