Presentation of a New Method for Quantitative Determination of Trifocal Intraocular Lens Decentration

Moreno Juan José[1,2], Galvis Virgilio[1,3], Salazar Mariana[3], Villamizar Sylvia Juliana[1,3,4], Leal Nathaly[3], Tello Alejandro[1,3-5]

[1]Faculty of Health, Department of Ophthalmology, Universidad Autónoma de Bucaramanga UNAB, Bucaramanga, Colombia

[2]Centro de Diagnóstico Ocular, Guayaquil, Ecuador

[3]Centro Oftalmologico Virgilio Galvis, Floridablanca, Colombia

[4]Departament of Ophthalmology, Fundacion Oftalmologica de Santander FOSCAL, Floridablanca, Colombia

[5]Faculty of Health, Department of Surgery, Universidad Industrial de Santander UIS, Bucaramanga, Colombia

Submitted to the editorial board: November 13, 2024
Accepted for publication: December 7, 2024
Available on-line: February 13, 2025

The authors declare that the present paper has not been simultaneously submitted to another journal and is not printed elsewhere. This study did not receive any funding from any institution. The study was not supported by any pharmaceutical company.

First author:
Juan José Moreno, MD

Corresponding author:
Alejandro Tello, MD, PhD
Centro Oftalmologico Virgilio Galvis.
FOSCAL Internacional
Calle 157 # 20 – 94, Torre C, Consultorio 301.
Cañaveral
Floridablanca – Santander
681004 Colombia
E-mail: alejandrotello@gmail.com

SUMMARY

Aims: This pilot study aims to present a novel method for quantitatively assessing the decentration of a trifocal intraocular lens (IOL) (Acrysof IQ PanOptix®) relative to three ocular reference points: the visual axis (first Purkinje reflex), the photopic pupil center, and, for the first time, the corneal geometric center. Additionally, the study evaluates the influence of postoperative chord mu, chord alpha, and the distances of the IOL from these reference points on visual outcomes.
Materials and Methods: This retrospective, observational study included 18 eyes from 12 patients who underwent cataract surgery with PanOptix® IOL implantation. Postoperative IOL positioning was assessed using OPD-Scan III images, applying a novel approach that combines diffuse frontal and retroillumination views. Distances between the IOL center and three ocular reference points, including the corneal geometric center, were measured, and postoperative patient satisfaction was evaluated using the Catquest-9SF survey. Statistical analyses were performed to assess correlations among reference distances, chord measurements, and visual performance.
Results: The study found that in 72.2% of cases, the IOL center was closer to the visual axis than to the corneal geometric center. A greater distance between the IOL and the corneal geometric center was associated with an improved near-vision area under the visual acuity defocus curve. However, no significant correlations were found between chord mu or chord alpha and visual outcomes, patient symptoms, or satisfaction.
Conclusion: This new approach to determining IOL centration proved practical, showing that the PanOptix® IOL tends to remain close to the visual axis over time, aligning with the surgeon's initial placement. No clear associations were found between chord mu, chord alpha, or most IOL distances (except the distance to the corneal geometric center) and visual quality or patient satisfaction. Further studies are needed to confirm these findings and to refine selection criteria for multifocal IOLs to enhance patient satisfaction and visual outcomes.
Key words: Trifocal intraocular lens, IOL decentration, corneal geometric center, visual axis, chord mu, chord alpha

Čes. a slov. Oftal., 81, 2025, No. x, p.

INTRODUCTION

Phacoemulsification surgery has advanced significantly with the development of multifocal intraocular lenses (IOLs), providing good vision at various distances and broadening the surgery's applications. It is now not restricted to cataract cases, but also used to correct ametropias and presbyopia in older adults [1,2]. This procedure, known as refractive lens exchange (RLE), demands careful patient selection, particularly when multifocal IOLs are implanted, and factors like the kappa and alpha angles may influence visual results and postoperative dysphotopsias [1,3–6]. Directly measuring these angles is challenging in clinical practice, so surrogate measurements like chord mu and chord alpha are used instead [4–6]. These two linear counterparts of the angles are measured by considering the intersections of different axes, or their surrogates, with the cornea and determining them as straight-line distances projected onto a two-dimensional plane. Chord mu is defined as the distance between the corneal intersection of the visual axis (approximated by the first Purkinje reflex) and the center of the pupil as seen from the fixation point (i.e., the intersection of the line of sight with the cornea). Conversely, chord alpha refers to the distance between the visual axis and the geometric center of the limbus, which serves as a surrogate for the optical axis of the eye. [4–6].

Research suggests that preoperative chord mu, and chord alpha may affect visual quality and symptoms after multifocal IOL implantation, although there is still debate about this relationship [7–21]. In addition, another factor, IOL centration, also seems to play a role in patient satisfaction, as it has been found that significant IOL decentration can lead to visual disturbances [21–33]. Quantitative evaluation of the position of multifocal IOLs relative to the first Purkinje reflex (a proxy for the visual axis) has been reported [27–33]. However, no publications have evaluated the IOL position relative to the corneal geometric center, a reference point considered significant by some researchers who suggest that multifocal IOLs may naturally tend to center near this point [7]. This pilot study introduces a novel method for measuring the decentration of trifocal IOLs (Acrysof IQ PanOptix®, Alcon) relative to the visual axis, pupillary center, and corneal geometric center using OPD-Scan III images. In addition, it evaluates the impact of postoperative chord mu and chord alpha on visual outcomes. [17,27–33].

MATERIALS AND METHODS

This was a retrospective, observational, and analytical study, based on the data available in an anonymized database of adult patients who underwent cataract surgery with the PanOptix® IOL. The surgeon (VG) intraoperatively attempted to align the center of the IOL with the first Purkinje reflex. Exclusion criteria included cases with intraoperative or postoperative complications and the presence of ocular diseases other than cataracts that could influence visual outcomes.

Postoperative patient satisfaction was assessed according to the validated Catquest-9SF survey. The determination of chord mu and chord alpha, as well as measurements of the decentration of the PanOptix® IOL with respect to the first Purkinje image, the center of the photopic pupil, and the geometric center of the cornea, were based on captures taken postoperatively with the OPD-Scan III aberrometer-topographer (Nidek). This device directly determines the apparent chord mu (referred to as "Photopic distance to center" or simply "PDist") and the chord alpha, which corresponds to the distance (chord) between the limbal center, representing the corneal geometric center used as an equivalent to the optical axis, and the first Purkinje reflex (a surrogate for the corneal intersection of the visual axis). This value is labeled by the OPD-Scan III, in the "WTW Information" section, as the "dist to center" or simply "LDist" (Figure 1).

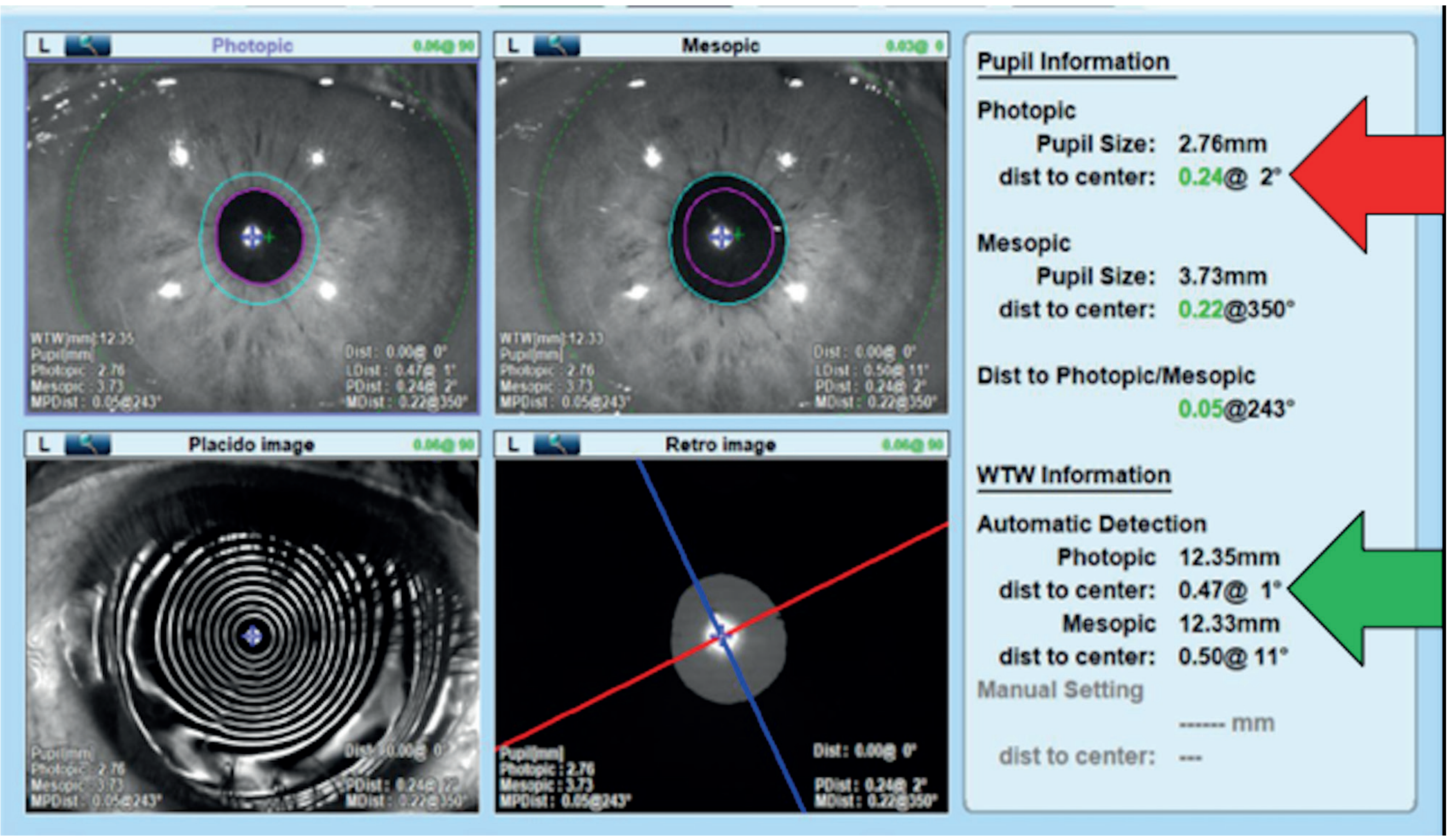


Figure 1. Results displayed by the OPD-SCAN III (Nidek) device, which features a Placido disc and a retinoscopic aberrometer. The apparent chord mu with the photopic pupil, expressed in mm in the figure (red arrow), as a substitute for the kappa angle, and the chord alpha, i.e. distance from the corneal geometric center to the first Purkinje reflex, expressed in mm in the figure, as a substitute for the alpha angle, also measured with the photopic pupil (green arrow), were used in this study

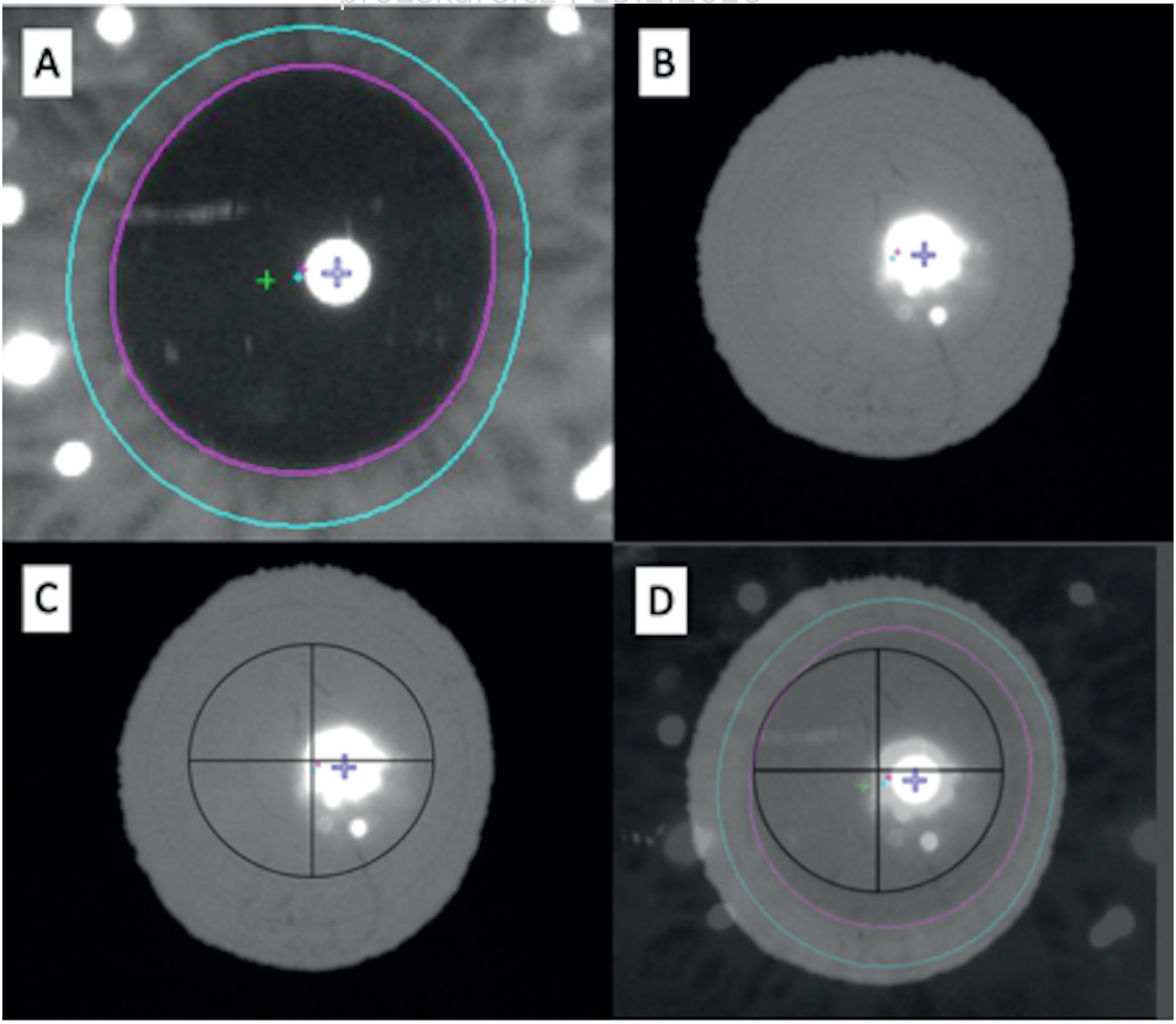


Figure 2. (**A**) Image with diffuse frontal illumination from the OPD SCAN III. Four points of interest are visible within the pupil, from left to right: corneal geometric center (green cross); mesopic pupil center (small blue cross); photopic pupil center (small magenta cross); first Purkinje reflex (violet cross). (**B**) Retroillumination image showing the diffractive concentric rings of the PanOptix® multifocal IOL, along with only three visible reference points. The corneal geometric center is not shown in the retroillumination image obtained with the OPD SCAN III. (**C**) A circle with two orthogonal diameters was drawn to determine the IOL center. (**D**) Images A and C were superimposed to reveal the four reference points of interest, as well as the center of the IOL

In the image taken with diffuse frontal illumination on the OPD-SCAN III, four reference points are marked: the surrogate of the visual axis (a violet cross within the first Purkinje reflex), the corneal geometric center (green cross), and the center of the pupil in two light conditions (photopic, indicated by a small magenta cross, and mesopic, marked by a small blue cross), as shown in Figure 2A. Additionally, the device captures a retroillumination image, in which the corneal geometric center is not marked, but the other three reference points are present. Thus, it is possible, with a simple image editor (such as the one included in Microsoft PowerPoint®), to precisely overlay the two images – diffuse frontal illumination and retroillumination – simply using the "image transparency" tool to align the three reference points visible in both images (Figure 2). This allows the creation of a new image in which, in addition to these three reference points (visual axis, photopic pupil center, and mesopic pupil center), the corneal geometric center, indicated only in the diffuse light image of the OPD-SCAN III but not in the retroillumination image, is also visible. In this study, using this composite image obtained by overlaying the photopic diffuse light image and the retroillumination image, with all reference points (visual axis, pupil center, and corneal geometric center) and, in addition, the center of the IOL optic visible, we utilized a public-domain image editing program available from the National Institutes of Health (ImageJ, https://imagej.net/ij/) to establish other distances of interest, both in magnitude and angle, using the system-determined measurements for chord mu and chord alpha distances as references, including those observed between the center of the multifocal IOL and the visual axis, the photopic pupil center, and the corneal geometric center (Figure 2).

The visual acuity (VA) defocus curve was also determined, following the correction of the residual refractive error, and ensuring refraction targeted to infinity, by adding -0.25 D to the refraction measured with the optotypes at 4 m. The Multifocal Lens Analyzer 3.0 application, version PRO, designed for iPad devices (Qvision, Almería, Spain), available at https://www.defocuscurve.com/es/, was used [34,35]. For this study, an iPad 10.2" (8th generation), with a screen size of 10.2 inches and a resolution of 2160 x 1620 pixels at 264 ppi served as the testing device to generate defocus curves. For the Multifocal Lens Analyzer 3.0 application, display contrast calibration involved disabling the automatic brightness setting to maintain consistent luminance. The app automatically adjusted the background luminance to meet standardized testing conditions. In this study, the default gamma settings were as follows: red: 2.19, green: 2.20, and blue: 2.22. The application operated at 41% brightness, corresponding to 85 cd/m^2. Sloan optotypes, with a letter size of 5.8 mm for the 20/20 optotype to comply with ETDRS chart standards, were used to evaluate various visual acuity levels and spatial frequencies expressed in cycles per degree. For a testing distance of 4 m, the system automatically calculated the required lens for a given defocus, by adding +0.25 D to the nominal defocus (in order to compensate for the negative vergence of the optotype located at 4 m). The Multifocal Lens Analyzer 3.0 PRO generates Contrast Sensitivity Defocus Curves by measuring contrast sensitivity at varying defocus levels. Using Sloan (ETDRS) optotypes for a 0.3 logMAR corresponding letter size (theoretical 15 cpd), presented at different contrast levels, the application randomizes the optotype sequence to prevent memorization and ensure reliability. At each defocus step, the patient's contrast sensitivity is recorded, and the application generates the curve to illustrate visual performance across different focal ranges. The defocus range used in both curves was between +1.00 and -4.00 D in 0.5 D steps. In addition, the application calculated the Area Under the Curve (AUC) to provide a quantitative summary of both visual acuity and contrast sensitivity performance, considering all measurements obtained without excluding any visual acuity or contrast sensitivity data. The AUC, a widely used metric for summarizing visual performance, is determined by integrating the curve generated from visual acuity or contrast sensitivity measurements over the full defocus range assessed in the tests. AUC values below 0.3 logMAR can be efficiently calculated using the trapezoidal numerical integration method, with the 0.5 D defocus steps normalized to a unit scale [35,36]. This metric summarizes the overall quality of vision provided by a specific lens or condition, offering a single value that represents total visual performance across various levels of acuity and contrast. Furthermore, the AUC was calculated separately for each defocus curve in the distant (+0.50 to -0.50 D), intermediate (-0.50 to -2.00 D), and near (-2.00 to -4.00 D) regions.

Statistical Analysis

The normality of quantitative variables was assessed graphically, using statistical estimates and the Shapiro-Wilk test. Measures of central tendency and dispersion of quantitative variables were estimated according to the frequency distribution. The alignment of the multifocal IOL with respect to the visual axis (first Purkinje reflex) and its relationship with the mu and alpha chords, as well as its influence on postoperative satisfaction and visual quality following cataract surgery, were evaluated. Pearson correlation tests were conducted for correlations between two normally distributed variables, and Spearman's Rho test was used for correlations involving one normally distributed variable and one non-normal distributed variable. Statistical analysis was performed with an alpha level of 0.05, using IBM SPSS Statistics for Windows, version 25.0.

Ethical Considerations

This research project adhered to the ethical guidelines outlined in the World Medical Association's Declaration of Helsinki, taking into account ethical principles for medical research involving human subjects, as described in Sections 9, 22, 23, and 24. Additionally, it complied with the regulations established by the Ministry of Health of Colombia in Resolution 008430 of October 4, 1993, Article 11, which classifies this project as a risk-free investigation, as it was a documentary study. Approval was granted by the Ethics Committee of FOSCAL.

RESULTS

The demographic information of the 12 patients (18 eyes) included in this pilot study, who were examined 15.7 months or more after multifocal PanOptix® IOL implantation, is shown in Table 1.

Table 2 presents the postoperative chord mu and chord alpha measurements (determined with the OPD SCAN III aberrometer) and the distances of the IOL center

Table 1. Demographic Information of Patients and Eye Characteristics

Patients – Total (men: women)	12 (2:10)
Age – mean ± standard deviation (years)	64.6 ±9.1
Eyes – Total (right:left)	18 (10:8)
Postoperative follow-up time – mean ± standard deviation; range – (months)	20.7 ±4.4 ; 15.7 to 27.9

Table 2. Average of Different Postoperative Metrics in Pseudophakic Eyes with Trifocal Intraocular Lens (PanOptix)

Parameter	Mean ±SD (µm)	Minimum (µm)	Maximum (µm)
Chord mu (first Purkinje reflex- photopic pupil center)	224 ±139	6	450
Chord Alpha (first Purkinje reflex- geometrical center of the cornea)	553 ±111	360	800
Distance IOL center to first Purkinje reflex	258 ±120	23	470
Distance IOL center to photopic pupil center	270 ±145	18	548
Distance IOL center to geometrical center of the cornea	416 ±201	42	739

IOL – Intraocular lens

Table 3. Relationship of the visual axis position* relative to the photopic pupil center and the corneal geometric center

Visual axis position*	Relative to the photopic pupil center (right eyes)	Relative to the photopic pupil center (left eyes)	Relative to the corneal geometric center (right eyes)	Relative to the corneal geometric center (left eyes)
Inferonasal	4 (40%)	1 (12.5%)	1 (10%)	4 (50.0%)
Inferotemporal	0 (0%)	0 (0%)	1 (10%)	1 (12.5%)
Superonasal	6 (60%)	6 (75%)	8 (80%)	2 (25.0%)
Superotemporal	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Temporal	0 (0%)	0 (0%)	0 (0%)	1 (12.5%)
Inferior	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Superior	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Nasal	0 (0%)	1 (12.5%)	0 (0%)	0 (0%)
TOTAL EYES	10	8	10	8

*Considered to be located at the first Purkinje reflex

Table 4. Position of the IOL Center Relative to Reference Points

IOL position	Relative to the visual axis* (right eye)	Relative to the visual axis* (left eye)	Relative to the corneal geometric center (right eyes)	Relative to the corneal geometric center (left yes)	Relative to the photopic pupil center (right eyes)	Relative to the photopic pupil center (left eyes)
Inferonasal	2 (20%)	1 (12.5%)	4 (40%)	4 (50.0%)	1 (10%)	1 (12.5%)
Inferotemporal	3 (30%)	4 (50.0%)	1 (10%)	1 (12.5%)	3 (30%)	3 (37.5%)
Superonasal	1 (10%)	0 (0%)	5 (50%)	2 (25.0%)	5 (50%)	3 (37.5%)
Superotemporal	4 (40%)	3 (37.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Temporal	0 (0%)	0 (0%)	0 (0%)	1 (12.5%)	0 (0%)	0 (0%)
Inferior	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (10%)	0 (0%)
Superior	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (11.1%)
TOTAL EYES	10	8	10	8	10	8

*Considered to be located at the first Purkinje reflex
IOL – Intraocular lens

relative to three reference points: the first Purkinje reflex (visual axis proxy), the corneal geometric center, and the photopic pupil center. In all eyes, the chord mu was of smaller magnitude than the chord alpha (mean difference 329 ±130 µm; difference range from 80 to 614 µm).

Regarding the distance from the IOL center to the first Purkinje reflex (visual axis proxy), two eyes had a distance of less than 100 µm. In terms of the distance from the IOL center to the corneal geometric center, only one eye had a distance of less than 100 µm. In 72.2% of the eyes, the distance from the IOL center to the first Purkinje reflex (visual axis proxy) was shorter than the distance from the IOL center to the corneal geometric center.

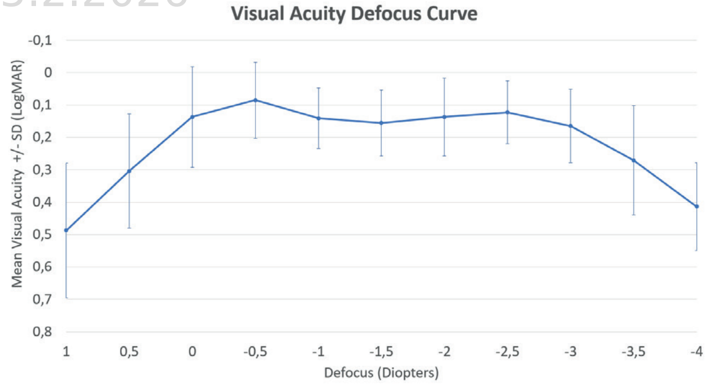
In all eyes, the visual axis (considered to be located at the first Purkinje reflex) was nasal relative to the pupil center, located in the superonasal quadrant in 60% of the right eyes and 75% of the left eyes (Table 3). The visual axis (considered at the first Purkinje reflex) was nasal to the corneal geometric center in 90% of the right eyes and 75% of the left eyes (Table 3). In all eyes, the corneal geometric center was located temporally relative to the pupil center.

The position of the multifocal IOL center relative to the visual axis (considered at the first Purkinje reflex), the photopic pupil center, and the corneal geometric center was analyzed (Table 4). Relative to the visual axis and considering both eyes, 77.8% of the center of the IOLs were located in a temporal position, and 22.2% in a nasal position. Relative to the corneal geometric center and considering both eyes, 83.3% of the center of the IOLs were located nasally, and 16.7% temporally. Relative to the photopic pupil center and considering both eyes, 55.6% of the center of the IOLs were located nasally, and 33.3% temporally (Table 4).

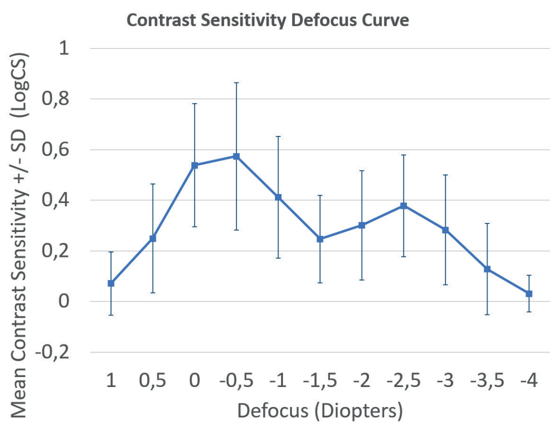
The VA defocus curve showed that within defocus ranges between -0.50 diopters (equivalent to a distance of 2 meters) and -3.00 diopters (equivalent to a distance of 33 centimeters), the eyes achieved a mean VA between 0.2 and 0.1 logMAR (Graph 1). The contrast sensitivity defocus curve is shown in Graph 2.

The correlation between corneal reference point distances, both among them and with the distances from the IOL center, was analyzed. Three statistically significant correlations were found: a moderate positive correlation between the chord mu and chord alpha (r = 0.475), a moderate positive correlation between the chord mu and the distance from the IOL center to the photopic pupil center (r = 0.579), and a moderate positive correlation between the distance from the IOL center to the photopic pupil center and the distance from the IOL center to the corneal geometric center (r = 0.606) (Table 5).

Regarding the defocus curves, the only significant correlation identified was a moderate one (Spearman correlation coefficient: 0.492) between the distance from the IOL center to the corneal geometric center and the AUC of the near-vision region of the VA defocus curve. No significant correlations were found either between the



Graph 1. The visual acuity defocus curve was established by correcting residual refractive error. The Multifocal Lens Analyzer 3.0 app for iPads (Qvision, Almería, Spain) was utilized. Within defocus ranges from -0.50 to -3.00 diopters (2 meters to 33 centimeters), the eyes maintained an average visual acuity between 0.2 and 0.1 logMAR



Graph 2. Contrast sensitivity defocus curve determined using the Multifocal Lens Analyzer 3.0 app, which uses ETDRS Charts with variable contrast. The defocus range used in was between +1.00 and -4.00 D in 0.5 D step

Table 5. Correlation between the distances of corneal reference points, among themselves and with the distances from the center of the intraocular lens

		Chord mu	Distance from IOL center to visual axis*	Chord Alpha	Distance from IOL center to corneal geometric center
Distance from IOL center to visual axis*	r	-0.030			
	P value	0.905			
Chord Alpha	r	**0.475**	-0.058		
	P value	**0.046****	0.821		
Distance from IOL center to corneal geometric center	r	0.396	0.000	0.141	
	P value	0.104	0.999	0.578	
Distance from IOL center to photopic pupil center	r	**0.579**	0.177	0.276	**0.606**
	P value	**0.012****	0.483	0.267	**0.008****

*Considered to be located at the first Purkinje reflex
**statistically significant p-value
r – Pearson correlation coefficient, IOL – Intraocular lens

AUC of the VA defocus curve, and the distances among other corneal reference points (chord mu, chord alpha, and corneal geometric center) or between the AUC and the distances from the IOL center to the three corneal reference points (first Purkinje reflex, photopic pupil center, and corneal geometric center). (Table 6). When analyzing the correlation between the AUC of the contrast sensitivity defocus curve and the distances of the corneal reference points (chord mu, chord alpha, corneal geometric center), as well as the distances from the IOL center to these reference points, no statistically significant correlations were detected (Table 7).

No significant correlations were found between the distances of the corneal reference points and the IOL center distances, with the level of satisfaction and visual symptoms of the patients (Table 8).

Table 6. Correlation between the distances of corneal reference points and the distances from the center of the intraocular lens, with the AUC of the visual acuity defocus curve

		AUC – Total	AUC – Distance Vision	AUC – Intermediate Vision	AUC – Near Vision
Chord Mu	r	0.264$^{\Psi}$	0.270$^{\Psi}$	0.060$^{\Phi}$	0.208$^{\Phi}$
	P value	0.290	0.278	0.813	0.408
Distance from IOL center to visual axis*	r	0.095$^{\Psi}$	0.311$^{\Psi}$	0.130$^{\Phi}$	-0.199$^{\Phi}$
	P value	0.707	0.209	0.606	0.427
Chord alpha	r	0.411$^{\Psi}$	0.146$^{\Psi}$	0.060$^{\Phi}$	0.236$^{\Phi}$
	P value	0.090	0.564	0.813	0.346
Distance from IOL center to corneal geometric center	r	0.409$^{\Psi}$	0.142$^{\Psi}$	0.062$^{\Phi}$	**0.492**$^{\Psi}$
	P value	0.092	0.574	0.807	**0.038****
Distance from IOL center to photopic pupil center	r	0.294$^{\Psi}$	0.091$^{\Psi}$	-0.029$^{\Phi}$	0.326$^{\Phi}$
	P value	0.236	0.719	0.909	0.187

*Considered to be located at the first Purkinje reflex
$^{\Psi}$: Calculated with Pearson correlation
$^{\Phi}$: Calculated with Spearman correlation
r – coefficient correlation, AUC – Area under the curve, IOL – Intraocular lens

Table 7. Correlation between the distances of corneal reference points and the distances from the center of the intraocular lens, with the AUC of the contrast sensitivity defocus curve

		AUC – Total	AUC – Distance Vision	AUC – Intermediate Vision	AUC – Near Vision
Chord mu	r	0.171$^{\Psi}$	0.076$^{\Psi}$	0.262$^{\Psi}$	0.145$^{\Phi}$
	P value	0.499	0.764	0.293	0.565
Distance from IOL center to visual axis*	r	0.059$^{\Psi}$	0.043$^{\Psi}$	-0.030$^{\Psi}$	0.115$^{\Phi}$
	P value	0.815	0.867	0.904	0.649
Chord alpha	r	0.446$^{\Psi}$	0.343$^{\Psi}$	0.453$^{\Psi}$	0.264$^{\Phi}$
	P value	0.064	0.163	0.059	0.289
Distance from IOL center to corneal geometric center	r	0.214$^{\Psi}$	0.189$^{\Psi}$	0.132$^{\Psi}$	0.339$^{\Phi}$
	P value	0.394	0.453	0.601	0.168
Distance from IOL center to photopic pupil center	r	0.260$^{\Psi}$	0.161$^{\Psi}$	0.326$^{\Psi}$	0.119$^{\Phi}$
	P value	0.298	0.524	0.187	0.637

*Considered to be located at the first Purkinje reflex
$^{\Psi}$: Calculated with Pearson correlation
$^{\Phi}$: Calculated with Spearman correlation
r – coefficient correlation, AUC – Area under the curve, IOL – Intraocular lens

Table 8. Correlation between the distances of corneal reference points and the distances from the center of the intraocular lens, with satisfaction level and visual symptoms

		Do you experience that your present vision is giving you difficulty in any way in your everyday life?	Are you satisfied or dissatisfied with your present vision?	Do you have problems with seeing halos around objects?	Do you have issues with seeing glare around lights?
Chord mu	r	0.026	0.231	-0.415	-0.362
	P value	0.920	0.357	0.087	0.141
Chord alpha	r	-0.207	0.209	-0.393	-0.370
	P value	0.411	0.405	0.107	0.132
Distance from IOL center to visual axis*	r	0.026	-0.209	0.168	0.105
	P value	0.919	0.406	0.507	0.679
Distance from IOL center to photopic pupil center	r	0.258	-0.055	0.080	-0.122
	P value	0.302	0.829	0.751	0.630
Distance from IOL center to corneal geometric center	r	0.232	0.209	-0.013	-0.152
	P value	0.355	0.406	0.958	0.546

IOL – Intraocular lens

DISCUSSION

The concept of chord mu (or kappa distance), introduced by Chang and Waring IV, refers to the distance between the pupil center and the first Purkinje reflex, viewed coaxially from the surgical microscope or the central camera of the measuring device [4]. The influence of chord mu on visual outcomes after multifocal IOL implantation remains a topic of debate.

Prakash et al. analyzed 50 eyes implanted with a Rezoom® bifocal IOL and found a significant association between preoperative chord mu and photic phenomena such as halos and glare. However, they also observed that some patients with large chord mu values did not present symptoms, suggesting that other factors also play a role [7]. In another prospective study, Qi et al. evaluated the visual quality of 89 patients after implantation of an AT LISA tri 839MP® trifocal IOL. They classified patients into three groups according to the magnitude of chord mu: Group A (0-200 µm), Group B (200-400 µm), and Group C (>400 µm). Although they did not find significant differences in VA between the groups, they did note an increase in the incidence of glare and halos in patients with chord mu values greater than 400 µm, and a decrease in visual quality when chord mu exceeded 500 µm [10].

Garzón et al. evaluated changes in chord mu after trifocal IOL implantation in pseudophakic eyes with it correctly centered in the capsular bag (although they did not specify how they determined IOL centration). They found no significant differences in refractive or VA outcomes between patients with postoperative chord mu ≤300 µm and >300 µm, and 87.5% of those reporting halos had a chord mu ≤300 µm. They concluded that chord mu did not affect visual outcomes [13]. In a prospective study, Velasco-Barona et al. evaluated the association between chord mu and postoperative VA in 43 patients with AT LISA tri 839MP® or PanOptix® trifocal IOLs. At six months, both groups achieved excellent VA at all distances, with no relationship found between postoperative chord mu and visual acuity [14]. Similarly, in a recent analysis of a large sample of 26,470 eyes, Wallerstein et al. concluded that chord mu had no clinically relevant impact on visual outcomes following the implantation of PanOptix® and FineVision® multifocal IOLs. The study determined that chord mu should not be used as the sole criterion for selecting candidates for multifocal IOLs, as it did not affect refractive accuracy or patient subjective satisfaction [16]. As for chord alpha, it measures the distance between the intersection of the visual axis and the corneal geometric center and serves as a surrogate for the alpha angle. Cervantes-Coste et al. and Qin et al. studied its impact on visual quality, finding that in patients with trifocal or extended depth of focus (EDOF) IOLs, a chord alpha greater than 400 µm may be associated with a higher incidence of halos and glare in low-light conditions, although it did not appear to directly affect visual acuity [37,38]. In another study by Fu et al., 7 out of 29 eyes with chord alpha greater than 500 µm reported bothersome visual symptoms, and the authors recommended careful consideration of IOL implantation in patients with large chord alpha values [11].

In the present study, a moderate positive correlation was observed between chord mu and chord alpha (r = 0.475), indicating a geometric relationship between these corneal reference points. This correlation suggests that shifts in chord mu are associated with variations in chord alpha, which could reflect a structural alignment that may influence certain aspects of corneal optics. However, we did not detect a direct impact of postoperative chord mu or chord alpha on the AUC of visual acuity or contrast sensitivity. It should be noted that the eyes included in this pilot study had a maximum chord mu of 450 µm and a chord alpha of 800 µm.

IOL centration has also been analyzed in various studies. Early studies were conducted on dissatisfied patients who had received a multifocal IOL. Woodward et al. found that IOL decentration in three of nine patients with ReSTOR® bifocal IOLs was related to visual dissatisfaction and dysphotopic phenomena [21]. De Vries et al. corroborated these findings by evaluating 49 dissatisfied patients with multifocal IOLs, 7 of whom showed decentration associated with reported visual symptoms [23]. In neither of these two studies did the researchers explain in detail how they determined the IOL decentration.

Experimental studies, such as that by Soda et al., have evaluated the influence of decentration on the optical performance of multifocal IOLs using laboratory eye models. In this study, the modulation transfer function (MTF) was measured in four types of multifocal IOLs with decentrations ranging from 0.25 mm to 1 mm. The results indicated that MTF and simulated near-vision images were affected to varying degrees by decentration in all four IOL models [24]. Karhanová et al. determined the critical kappa angle for four bifocal IOLs, suggesting that patients with a large kappa angle are at higher risk of photic phenomena, especially if the IOL is temporally decentered relative to the pupillary center [18].

There are not many clinical studies that have quantitatively or semi-quantitatively established the centration of a multifocal IOL and its impact on visual quality. Fuentes et al. in 2009 found, in patients implanted with a bifocal IOL (ReSTOR®, Alcon), that third-order coma aberration showed significant differences depending on the location of the IOL center relative to the pupil center, as determined by corneal tomography imaging (Galilei, Ziemer). The magnitude of this aberration was larger when the IOL center was decentered toward the temporal quadrants [25]. Karhanová et al. subjectively evaluated the centration of a bifocal IOL (ReSTOR®, Alcon) in 26 patients at the slit lamp relative to the pupil center and suggested an interaction between IOL centration and the kappa angle (measured with a synoptophore). According to their results, temporal decentration of the bifocal IOL relative to the pupil center was associated with a higher risk of visual symptoms (photic phenomena), particularly in cases with a larger kappa angle [26].

Fernández et al. observed that a temporal decentration of up to 550 µm from the normal vertex, determined by semi-quantitative analysis of a slit-lamp retroillumination photograph, improved intermediate VA in patients with Bi-Flex M 677MY® multifocal IOLs. This finding contrasts with previous studies suggesting that decentrations negatively affect visual quality [39]. He et al. evaluated the decentration and tilt of ReSTOR® and Tecnis® ZMB00 multifocal IOLs one year after surgery, using images from the OPD-Scan III aberrometer, with the first Purkinje reflex (a proxy for the visual axis intersection with the cornea) as the reference for determining IOL centration. They found that IOL tilt affected higher-order aberrations (HOAs), but no significant correlation was found between IOL decentration and HOAs in the ReSTOR® group, while in the Tecnis® group, a positive correlation was observed between decentration and HOAs. They did not measure IOL decentration relative to another reference point (pupil center or corneal geometric center) [17]. In another study by Xu et al., it was found that a decentration greater than 250 µm (also determined with respect to the first Purkinje reflex, a surrogate for the visual axis, using the OPD-Scan III aberrometer) significantly deteriorated visual quality in eyes with Tecnis® bifocal IOLs, while the monofocal and EDOF IOLs from the same manufacturer showed greater tolerance to decentration [33]. This same research group, in a study on monofocal IOL decentration, also used the OPD-Scan III to assess the magnitude and orientation of decentration relative to the visual axis. They determined that white-to-white distance and chord alpha were associated with greater decentration. In addition, the horizontal components of chord mu and chord alpha were related to horizontal decentration, while anterior chamber depth and the vertical component of chord mu were related to vertical decentration [40]. Meng et al. compared the centration of two multifocal IOLs, also with respect to the visual axis, and observed that myopic eyes with Tecnis® IOLs showed greater vertical and general decentration compared to AT Lisa® IOLs. In these eyes, axial length was negatively correlated with vertical decentration and positively correlated with general decentration [32]. Fernández et al. studied the relationship between the centration of trifocal IOLs (with reference to the corneal vertex, i.e., the first Purkinje reflex) and visual quality, by measuring the ocular scatter index (OSI) and light distortion index (LDI). Although there was no significant correlation between chords mu and alpha with these parameters, LDI was associated with the temporal position of the IOL center in relation to the visual axis. The authors suggested that temporal centration of the multifocal IOL with respect to the visual axis might be associated with a reduction in LDI, potentially leading to fewer photic phenomena, which agreed with other research by the same group of authors [39]. This concept, however, contrasts with the views of other researchers, who have suggested that aligning the center of the multifocal IOL with the visual axis may be preferable [7,26]. Fernández et al. concluded that further research with extreme values of these variables (chords mu and alpha, and IOL distance from the visual axis) is needed to establish exclusion criteria for multifocal IOL implantation. They did not analyze the position of the multifocal IOL center relative to the corneal geometric center [15].

In the present study, the mean postoperative chord mu was 224 ±139 µm, higher than that reported in two studies by Fernandez et al. (104 ±192 and 180 ±100 µm) [15,39], similar to that reported by Garzón et al. (200 ±120 µm) [13] and by Cervantes-Coste et al. (240 ±110 µm) [37], but lower than that found by Velasco-Barona et al. (337 ±150 µm in eyes with PanOptix® IOLs and 278 ±130 µm in eyes with AT LISA Tri® IOLs) [14]. The postoperative chord alpha was 553 ±111 µm, somewhat higher than that found by Qin et al. (370 ±130 µm) [38] and by Fernandez et al. (410 ±190 µm) [15], but lower than that found by Cervantes-Coste et al. (610 ±290 µm) [37]. On average, in the present study, chord alpha was approximately 2.5 times larger than chord mu.

As previously mentioned, a moderate positive correlation was detected between chord mu and chord alpha, meaning that as chord mu increases, chord alpha also tends to increase. Since both chord mu and chord alpha use the visual axis as a reference point, and this axis is generally positioned nasally with respect to the pupil center (reference point for chord mu) and the corneal geometric center (reference point for chord alpha), the positive correlation between the two chords suggests consistency in the nasal orientation of the visual axis, supporting the notion that the visual axis tends to be the most nasal of the three reference points. Regarding the magnitudes of multifocal IOL decentrations relative to the first Purkinje reflex (as a surrogate for the visual axis), Fernandez et al. reported an average of 300 ±190 µm for the Liberty Q-Flex M 640PM® or Liberty 677MY® (Medicontur Medical Engineering Ltd.) IOLs [15], while He et al. found an average of 350 ±170 µm for the ReSTOR® IOL and an average of 360 ±140 µm for the Tecnis ZMB00® IOL. These values were greater than the average of 258 ±120 µm distance from the IOL center to the first Purkinje reflex found in the present pilot study [17]. Xu et al. found decentration values relative to the first Purkinje reflex similar to those determined in the present study: 260 ±130 µm, 250 ±10 µm, and 250 ±150 µm, for eyes with Tecnis® monofocal, Tecnis® EDOF, and Tecnis® bifocal IOLs, respectively [33].

In the present pilot study, using the described approach based on images from the OPD-SCAN III for quantitative evaluation of IOL centration, a moderate positive correlation was found between chord mu and the distance from the IOL center to the photopic pupil center. Since chord mu represents the distance between the visual axis and the pupil center, a larger chord mu implies a more nasal position of the visual axis relative to the pupil center. Given the positive correlation with the distance between the IOL center and the photopic pupil center, it suggests that in eyes with larger chord mu values, the IOL center may indeed align more closely with the visual axis and be situated farther from the photopic pupil center. This could indeed be related to the surgeon's attempt to center the IOL along the visual axis. In addition, a moderate positive correlation was also found between the distance from the IOL center to the photopic pupil center, and the distance from the IOL center to the corneal geometric center, suggesting that as the IOL center is positioned farther from one of these points (e.g., the photopic pupil center), it is also likely to be farther from the other point (the corneal geometric center). The surgeon's attempt to position the IOL center closer to the visual axis would naturally increase its distance from both the photopic pupil center and the corneal geometric center, aligning with the observed correlation. This finding also suggests that the IOL tends to maintain a position close to the one intended by the surgeon.

Finally, the present study found that the mean distance from the IOL to the corneal geometric center was 1.6 times greater than the mean distance from the IOL to the visual axis, and in more than 70% of the eyes, the distance from the IOL center to the visual axis was shorter than the distance from the IOL center to the corneal geometric center.

In summary, the previously mentioned correlations and findings suggest that intraoperative centration of a multifocal IOL on the first Purkinje reflex does not result in alignment with the corneal geometric center, as some researchers have suggested [7], at least for the PanOptix® multifocal IOL platform used in this pilot study. Instead, the PanOptix® IOL tended to remain closer to the visual axis, where the surgeon initially positioned it, even in the mid- to long-term after surgery (mean 20.7 ±4.4 months). This contrasts with the opinions of other researchers, who have suggested that, due to multiple factors – including capsular contraction, IOL haptic memory, and postoperative IOL rotation – it is unlikely that a multifocal IOL centered intraoperatively on the visual axis would remain in the same position over time [7]. Clearly, there is not yet a definitive answer to this issue. Prospective studies with rigorous evaluation and documentation of intraoperative and postoperative IOL positioning are needed. Furthermore, the stability of the IOL in its original position may be influenced by many variables, including the IOL's optic and haptic design, its material, its interaction with the capsular bag postoperatively, the size of the capsular bag, and the amount of ophthalmic viscosurgical device left in the bag at the end of surgery.

Although, as mentioned, we did find some studies quantitively analyzing the location of the multifocal IOL center relative to the visual axis (i.e., first Purkinje reflex) with different approaches [15,17,33,41], we did not find any study analyzing the decentration of multifocal IOLs relative to the corneal geometric center, which we consider a significant contribution of our approach.

With regard to visual performance, we found a moderate positive correlation between the distance from the IOL center to the corneal geometric center and the AUC of the near vision area of the VA defocus curve. In other words, a larger AUC in the near vision area of the VA defocus curve was associated with a greater distance between the IOL center and the corneal geometric center. Therefore, it seems preferable for optimizing the AUC of the near vision area that the IOL center is positioned farther from the corneal geometric center (and then closer to the visual axis). However, this correlation does not establish causation, so other factors should also be considered in evaluating and positioning IOLs for optimal vision outcomes. Furthermore, this correlation was not significantly associated with overall satisfaction or visual symptoms.

CONLUSIONS

In conclusion, the impact of the magnitude of chord mu and chord alpha, as well as the centration of the IOL relative to the first Purkinje reflex and the corneal geometric center, and their potential association with visual outcomes and patient satisfaction, warrant further research. In this pilot study, we demonstrated that all these parameters can be easily determined by superimposing direct illumination and retroillumination images from the OPD SCAN III aberrometer. We did not find clear associations between chord mu and chord alpha with visual quality or patient satisfaction. Our results suggest that, at least with the PanOptix® IOL platform, it tends to remain centered near the visual axis, where the surgeon originally implanted it, and does not spontaneously shift toward the geometric center of the cornea (a theoretical surrogate for the topographical center of the capsular bag).

Additional studies are undoubtedly needed, but our findings established the feasibility of this approach to determine the centration of a multifocal IOL relative to three reference points (first Purkinje reflex, pupil center, and corneal geometric center), and this information may be very useful in analyzing a larger sample of patients implanted with multifocal IOLs.

ACKNOWLEDGMENTS

We would like to express our gratitude to Dr. Manuel Rodriguez-Vallejo and all the members of the R&D Department of Qvision Clinics in Almería, Spain, for their invaluable support in training us to use the Multifocal Lens Analyzer 3.0 application for this study.

REFERENCES

1. Galvis V, Escaf LC, Escaf LJ, et al. Visual and satisfaction results with implantation of the trifocal Acrysof IQ PanOptix® intraocular lens in cataract surgery. J Optom. 2022;15(3):219-227.
2. Zhu Y, Zhong Y, Fu Y. The effects of premium intraocular lenses on presbyopia treatments. Adv Ophthalmol Pract Res. 2022;2(1):100042.
3. Moshirfar M, Tuttle JJ, Stoakes IM, Hoopes PC. Refractive lens exchange: weighing the implications of early crystalline lens removal. J Cataract Refract Surg. 2023;49(10):1071-1072.
4. Chang DH, Waring GO 4th. The subject-fixated coaxially sighted corneal light reflex: a clinical marker for centration of refractive treatments and devices. Am J Ophthalmol. 2014;158(5):863-874.
5. Holladay JT. Apparent chord mu and actual chord mu and their clinical value. J Cataract Refract Surg. 2019;45(8):1198-1199.
6. Wang L, Guimaraes de Souza R, Weikert MP, Koch DD. Evaluation of crystalline lens and intraocular lens tilt using a swept-source optical coherence tomography biometer. J Cataract Refract Surg. 2019;45(1):35-40.
7. Prakash G, Prakash DR, Agarwal A, Kumar DA, Agarwal A, Jacob S. Predictive factor and kappa angle analysis for visual satisfaction in patients with multifocal IOL implantation. Eye (Lond). 2011;25(9):1187-1193.
8. Holladay JT, Zhao H, Reisin CR. Negative dysphotopsia: the enigmatic penumbra. J Cataract Refract Surg. 2012;38(7):1251-1265.
9. Holladay JT, Simpson MJ. Negative dysphotopsia: Causes and rationale for prevention and treatment. J Cataract Refract Surg. 2017;43(2):263-275.
10. Qi Y, Lin J, Leng L, et al. Role of angle κ in visual quality in patients with a trifocal diffractive intraocular lens. J Cataract Refract Surg. 2018;44(8):949-954.
11. Fu Y, Kou J, Chen D, et al. Influence of angle kappa and angle alpha on visual quality after implantation of multifocal intraocular lenses. J Cataract Refract Surg. 2019;45(9):1258-1264.
12. Sandoval HP, Potvin R, Solomon KD. The Effects of Angle Kappa on Clinical Results and Patient-Reported Outcomes After Implantation of a Trifocal Intraocular Lens. Clin Ophthalmol. 2022;16:1321-1329.
13. Garzón N, García-Montero M, López-Artero E, et al. Influence of angle κ on visual and refractive outcomes after implantation of a diffractive trifocal intraocular lens. J Cataract Refract Surg. 2020;46(5):721-727.
14. Velasco-Barona C, Corredor-Ortega C, Mendez-Leon A, et al. Influence of Angle κ and higher-order aberrations on visual quality employing two diffractive trifocal IOLs. J Ophthalmol. 2019;2019:7018937.
15. Fernández J, Burguera N, Rocha-de-Lossada C, Rachwani-Anil R, Rodríguez-Vallejo M. Influence of a multifocal intraocular lens centration and eye angles on light distortion and ocular scatter index. Graefes Arch Clin Exp Ophthalmol. 2023;261(8):2291-2299.
16. Wallerstein A, Ridgway C, Gatinel D, et al. Angle kappa influence on multifocal IOL outcomes. J Refract Surg. 2023;39(12):840–849.
17. He W, Qiu X, Zhang S, et al. Comparison of long-term decentration and tilt in two types of multifocal intraocular lenses with OPD-Scan III aberrometer. Eye (Lond). 2018;32(7):1237-1243.
18. Karhanová M, Pluháček F, Mlčák P, Vláčil O, Šín M, Marešová K. The importance of angle kappa evaluation for implantation of diffractive multifocal intra-ocular lenses using pseudophakic eye model. Acta Ophthalmol. 2015;93(2): e123-e128, doi: 10.1111/aos.12521
19. Wang R, Long T, Gu X, Ma T. Changes in angle kappa and angle alpha before and after cataract surgery. J Cataract Refract Surg. 2020;46(3):365-371.
20. Umesh Y, Saolapurkar K, Joshi P, Singh D. Measurement of change in angle kappa and its correlation with ocular biometric parameters pre- and post-phacoemulsification. Indian J Ophthalmol. 2023;71(2):535-540.
21. Woodward MA, Randleman JB, Stulting RD. Dissatisfaction after multifocal intraocular lens implantation. J Cataract Refract Surg. 2009;35:992-927.
22. Leysen I, Bartholomeeusen E, Coeckelbergh T, Tassignon MJ. Surgical outcomes of intraocular lens exchange: five-year study. J Cataract Refract Surg. 2009;35:1013-1018.
23. de Vries NE, Webers CA, Touwslager WR, et al. Dissatisfaction after implantation of multifocal intraocular lenses. J Cataract Refract Surg. 2011;37(5):859-865.
24. Soda M, Yaguchi S. Effect of decentration on the optical performance in multifocal intraocular lenses. Ophthalmologica. 2012;227(4):197-204.
25. Fuentes V, Galvis V, Tello A. Acrysoft ReSTOR esférico vs Acrysoft ResSTOR asférico: Centramiento y efecto sobre la calidad visual objetiva y subjetiva del paciente. Revista Sociedad Colombiana de Oftalmología. 2009;42(1):887-901.
26. Karhanová M, Marešová K, Pluháček F, Mlčák P, Vláčil O, Šín M. Význam úhlu kappa pro centraci multifokálních nitroočních čoček. [The importance of angle kappa for centration of multifocal intraocular lenses]. Cesk Slov Oftalmol. 2013;69(2):64-68. Czech.
27. Chen X, Gu X, Wang W, et al. Characteristics and factors associated with intraocular lens tilt and decentration after cataract surgery. J Cataract Refract Surg. 2020;46(8):1126-1131.
28. Kimura S, Morizane Y, Shiode Y, et al. Assessment of tilt and decentration of crystalline lens and intraocular lens relative to the corneal topographic axis using anterior segment optical coherence tomography. PLoS One. 2017;12(9)
29. de Castro A, Rosales P, Marcos S. Tilt and decentration of intraocular lenses in vivo from Purkinje and Scheimpflug imaging. Validation study. J Cataract Refract Surg. 2007;33(3):418-429.
30. Wang X, Dong J, Wang X, Wu Q. IOL tilt and decentration estimation from 3-dimensional reconstruction of OCT image. PLoS One. 2013;8(3):e59109.
31. Ashena Z, Maqsood S, Ahmed SN, Nanavaty MA. Effect of Intraocular Lens Tilt and Decentration on Visual Acuity, Dysphotopsia and Wavefront Aberrations. Vision (Basel). 2020;4(3):41.

32. Meng J, He W, Rong X, Miao A, Lu Y, Zhu X. Decentration and tilt of plate-haptic multifocal intraocular lenses in myopic eyes. Eye Vis (Lond). 2020;7:17.
33. Xu J, Zheng T, Lu Y. Effect of Decentration on the Optical Quality of Monofocal, Extended Depth of Focus, and Bifocal Intraocular Lenses. J Refract Surg. 2019;35(8):484-492.
34. Rodríguez-Vallejo M, Llorens-Quintana C, Furlan WD, Monsoriu JA. Visual acuity and contrast sensitivity screening with a new iPad application. Displays. 2016; 44:15-20.
35. Fernández J, Rodríguez-Vallejo M, Tauste A, Albarrán C, Basterra I, Piñero D. Fast measure of visual acuity and contrast sensitivity defocus curves with an iPad application. Open Ophthalmol. J. 2019;1:15-22.
36. Fernández J, Ribeiro FJ, Rodríguez-Vallejo M, et al. Standard for collecting and reporting outcomes of IOL-based refractive surgery: update for enhanced monofocal, EDOF, and multifocal IOLs. J Cataract Refract Surg. 2022;48(11):1235-1241.
37. Cervantes-Coste G, Tapia A, Corredor-Ortega C, et al. The Influence of Angle Alpha, Angle Kappa, and Optical Aberrations on Visual Outcomes after the Implantation of a High-Addition Trifocal IOL. J Clin Med. 2022;11(3):896.
38. Qin M, Ji M, Zhou T, et al. Influence of angle alpha on visual quality after implantation of extended depth of focus intraocular lenses. BMC Ophthalmol. 2022;22(1):82.
39. Fernández J, Rodríguez-Vallejo M, Martínez J, Tauste A, Piñero DP. Biometric Factors Associated with the Visual Performance of a High Addition Multifocal Intraocular Lens. Curr Eye Res. 2018;43(8):998-1005.
40. Xu J, Lin P, Zhang S, Lu Y, Zheng T. Risk Factors Associated With Intraocular Lens Decentration After Cataract Surgery. Am J Ophthalmol. 2022;242:88-95. doi:10.1016/j.ajo.2022.05.005
41. Polit F, Polit A, Polit J. Method to quantify the decentration of the multifocal intraocular lenses in relation to the visual axis in eyes following phacoemulsification. Vision Pan-America. 2018:17 (4):117-119.