

Article

Effect of Decentration on Aberrometric Profile of Rotationally Asymmetric Acunex Intraocular Lenses

Celia Villanueva ¹ , César Albarrán-Diego ^{2,*} , María García-Montero ¹ and Nuria Garzón ¹ 

¹ Department of Optometry and Vision, Faculty of Optics and Optometry, Complutense University of Madrid, 28037 Madrid, Spain; cevill02@ucm.es (C.V.); mgarc01@ucm.es (M.G.-M.); mgarzonj@ucm.es (N.G.)

² Department of Optics and Optometry and Vision Sciences, Faculty of Physics, Valencia University, 46100 Burjassot, Spain

* Correspondence: cesar.albarran@uv.es

Featured Application

Findings of the present study provide further optical insight into the behavior of this lens platform under non-ideal positioning conditions and may help to better understand its functional tolerance to misalignment, with potential implications for lens design assessment and clinical interpretation.

Abstract

The optical performance of rotationally asymmetric multifocal intraocular lenses (IOLs) may be especially vulnerable to decentration due to their non-rotationally symmetric refractive design. This study explores the effect of controlled decentration of IOLs on the aberrometric behavior of low-addition and high-addition Acunex IOLs. Both IOLs were evaluated on an optical bench using the NIMO system in centered position and under induced decentrations of 0.5 mm and 1.0 mm applied in horizontal and vertical directions. Average Zernike coefficients were analyzed for two apertures intended to represent smaller and larger pupil conditions. Both lenses showed similar aberrometric profiles under centered conditions and for the smaller aperture. However, with increasing decentration, the larger aperture revealed evident direction-dependent performance. The induced changes followed structured patterns that differed by magnitude and direction of decentration. The most noticeable variations were observed in asymmetric aberrations, particularly coma-related, while spherical aberration also changed under specific displacements. Although both IOLs shared similar trends, their responses differed, suggesting that the addition profile may influence decentration tolerance. Controlled decentration produces measurable, direction-dependent changes in the aberrometric profile of rotationally asymmetric Acunex IOLs, especially for larger aperture.

Keywords: aberrometric profile; decentration; intraocular lens; rotationally asymmetric



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1. Introduction

Cataract is defined as an opacification of the crystalline lens that mainly affects visual acuity, typically progresses over time, and shows a prevalence that is strongly associated with age [1]. Presbyopia is also age-related, with its prevalence increasing markedly in older populations. These age-related conditions have driven the development of advanced intraocular lenses (IOLs) that provide spectacle independence and functional vision across multiple distances [2]. Compared with conventional monofocal IOLs, multifocal IOLs

distribute light across multiple focal points, improving vision at different distances and reducing spectacle dependence [3,4].

In parallel with multifocal designs, extended depth of focus (EDoF) IOLs have been developed to provide a more continuous range of vision by elongating the focal point, thereby improving intermediate and functional near vision [5]. This optical performance is achieved through different optical strategies, such as pinhole, diffractive, non-diffractive, and zonal refractive designs [6].

Currently, cataract surgery is performed at an earlier stage and increasingly follows a refractive approach aimed at presbyopia correction, resulting in a longer expected duration of IOL implantation and a higher cumulative risk of decentration. Several factors may contribute to this phenomenon, including surgical aspects such as large or asymmetric capsulorhexis and capsular fibrosis [7,8], ocular conditions such as pseudoexfoliation, Marfan's syndrome or trauma [9,10], as well as haptic design and previous surgical procedures like vitrectomy [11,12]. Although modern surgical techniques have significantly reduced this complication, proper capsular centration and IOL stability remain essential to minimize postoperative decentration, which may also be influenced by subsequent interventions such as Nd:YAG capsulotomy [13].

Decentration and tilt of an IOL can significantly impair visual quality, reducing visual acuity, increasing intraocular aberrations and reducing contrast sensitivity. Presbyopia-correcting IOLs are more sensitive to decentration and tilt compared with monofocal IOLs [14,15]. Even small misalignments, less than 0.5 mm of decentration or low degrees of tilt, can induce noticeable visual symptoms such as glare, halos, astigmatism, or monocular diplopia, while larger misalignments lead to substantial vision loss. The impact of these effects depends, among other factors, on the IOL design, as different IOL designs exhibit different tolerances to decentration and tilt. Given the increasing use of presbyopia-correcting designs to enhance quality of life, it is critical to understand the effects of IOL decentration, especially in these types of designs [16]. The Acunex AN6V and AN6VM IOLs (Teleon Surgical, Spankeren, The Netherlands) are refractive presbyopia-correcting IOLs with a rotationally asymmetric optical design. Both models incorporate two distinct refractive regions arranged in opposite sectors of the optic. One region provides the distance focus, whereas the opposite segment contains the added power and provides intermediate and/or near focus, depending on the model. Thus, intermediate and/or near vision is achieved through the added-power segment, while distance vision is provided by the complementary distance-power region [17].

The aim of this study was to evaluate the impact of decentration on the aberrometric behavior of two presbyopia-correcting IOLs sharing the same platform and material: the Acunex AN6V, with a +1.50 D addition, and AN6VM, with a +3.00 D addition, both with a base power of +20.00 D. The analysis focuses on how decentration affects optical performance by assessing Zernike aberrations across two optical zones, 3.0 and 4.5 mm, which correspond to typical photopic and mesopic pupil sizes. A distinctive feature of these rotationally asymmetric designs is the presence of a notch within the added-power segment, which allows the central pupillary area to retain distance power. Therefore, decentration of the IOL may alter the relative alignment between the pupil center, the distance-power region, and the added-power segment, resulting in an uneven distribution of distance and near optical zones within the pupil. These IOLs had been previously analyzed by other authors [17] in a centered position at different powers (+10.00, +20.00 and +30.00 D). In the present study, induced decentrations of 0.5 mm and 1.0 mm along horizontal axis (x) and vertical axis (y, -y) were applied to investigate the resulting changes.

Although the qualitative link between decentration and coma induction has been established for other rotationally asymmetric multifocal IOLs, decentration tolerance had

not previously been characterized for the Acunex platform, which differs from previously studied segmented designs in both its eccentric notch geometry and its hydrophobic acrylate material, as opposed to the hydrophilic material of most previously characterized segmented platforms, a factor that influences achievable surface tolerances at the sector boundary. Comparing the low addition AN6V and high addition AN6VM versions of the same platform further allows this study to test, for the first time in a matched-platform pair, whether added power modulates decentration tolerance.

2. Materials and Methods

This study was carried out at the laboratory facilities of the Optics and Optometry Faculty of the University Complutense of Madrid, Spain.

2.1. Intraocular Lenses

The Acunex IOLs (Teleon Surgical, Spankeren, The Netherlands) analyzed in this study were the AN6V and AN6VM models. Both are one-piece posterior chamber IOLs composed of hydrophobic, glistening-free acrylate material with a high refractive index (1.54) and an additional ultraviolet- and blue-light-absorbing filter. They featured a step-vaulted C-loop design, an optical zone of 6.0 mm, and an overall diameter of 12.5 mm.

The AN6V [18] design is an EDoF IOL with a biconvex optic incorporating an anterior sector-shaped intermediate-vision segment of +1.50 D addition. The AN6VM [19] shares the same biconvex optic platform but features a sector-shaped intermediate and near vision segment with a +3.00 D addition instead. Both IOLs have an aspherical posterior surface with a neutral spherical aberration profile.

These IOLs incorporate two distinct refractive regions arranged in opposite sectors of the optic. One region provides the distance focus, whereas the opposite segment contains the intermediate and near addition and provides the intermediate and near focus. Thus, intermediate and/or near vision is achieved through the added-power segment, while distance vision is provided by the complementary distance-power region. In addition, these designs include a central notch containing the distance power, characterized by a reduced size, approximately 0.12 mm inferior to the optical center (Figure 1), which makes the lens notably sensitive to decentration between the notch and the pupil.

2.2. Optical Bench

The present analysis was scoped a priori to Zernike polynomial decomposition and the derived RMS metrics, deliberately consistent with the methodological framework used for the centered-position characterization of this same platform [17], so that both studies remain directly comparable term by term.

The optical performance of the IOLs was evaluated using the NIMO TR1504 device (LAMBDA-X, Nivelles, Belgium) operated with software version 2.17.3, which operates based on a combination of the Schlieren principle and phase-shifting interferometry method [20], enabling the acquisition of ray deviation data and subsequent reconstruction of the emerging wavefront. The resulting wavefront information is expressed through Zernike polynomial decomposition at the desired optical diameter, allowing a detailed analysis of optical aberrations.

Measurements were conducted using a monochromatic light source with a peak wavelength of 546 nm, which closely aligns with the peak spectral luminous efficiency of the human visual system, positioned at 555 nm in photopic conditions. Following established protocol for IOL assessment published by Gómez-Pedrero et al. [21], 10 series of repeated measurements were performed for each intraocular lens under in vitro conditions, in which the intraocular lenses were treated as thin optical elements. To simulate physiological con-

ditions and preserve intraocular lens integrity, all lenses were immersed in a saline solution ($n = 1.334$) within an aberration-free quartz cuvette. Optical performance was analyzed for optical zones of 3.0 mm and 4.5 mm, representing typical photopic and mesopic conditions, respectively. Repeatability of the NIMO measurement protocol, based on 10 repeated series per lens and condition, has been previously established and published [21].

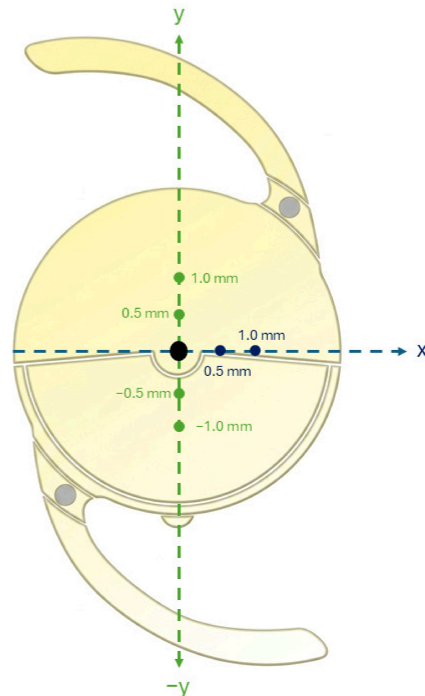


Figure 1. Schematic representation of Acunex multifocal intraocular lens (IOL) with the reference position of the IOL on the optical bench and the indication of the measurement axes (x and y) and the orientation used throughout the experimental measurements. The added-power segment is located inferiorly (i.e., toward the $-y$ direction), relative to the distance segment and the notch. The labels ± 0.5 mm and ± 1.0 mm denote the applied decentration magnitudes. The figure is illustrative only and is not to scale.

The IOL was positioned on the optical bench in the position shown in Figure 1. Decentration of the IOL was not performed manually: the target displacement value was entered directly into the NIMO (version 2.17.3) control software, which automatically drove the lens-support platform to the corresponding position, removing operator-dependent positioning variability. This positioning is a critical aspect of the methodology, as the measured optical performance depends on the orientation and alignment of the IOL with respect to the reference coordinate system. Firstly, the IOLs were measured under centered conditions relative to the optical axis; subsequently, decentrations were introduced to evaluate their optical performance. Measurements were performed with displacements of 0.5 mm and 1.0 mm along the horizontal axis (D05(x), D10(x)), and 0.5 mm and 1.0 mm along the vertical axis (D05(y), D05($-y$), D10(y), D10($-y$)).

3. Results

Table 1 summarizes the numerical Zernike coefficients and RMS values obtained for both IOL designs, both optical zones, and all decentration conditions evaluated. These data underlie the graphical representations shown in Figures 2–4 and are discussed in detail below.

Table 1. Numerical Zernike coefficients and RMS values (μm) for both IOL designs, both optical zones, and all decentration conditions evaluated. C: centered; D05/D10: 0.5 mm/1.0 mm decentration; x, y, $-y$: direction of decentration.

Lens	Optical Zone (mm)	Position	Primary SA Z(4:0)	Secondary SA Z(6:0)	RMS Spherical	Secondary Vertical Coma Z(5:−1)	Primary Vertical Coma Z(3:−1)	Primary Horizontal Coma Z(3:1)	Secondary Horizontal Coma Z(5:1)	RMS Coma	RMS HOA
AN6V (Add +1.50 D)	3	C	0.008 ± 0.000	-0.016 ± 0.000	0.017 ± 0.000	-0.021 ± 0.000	0.113 ± 0.000	0.003 ± 0.000	-0.000 ± 0.000	0.115 ± 0.000	0.175 ± 0.000
AN6V (Add +1.50 D)	3	D05(x)	-0.006 ± 0.000	0.001 ± 0.000	0.006 ± 0.000	-0.012 ± 0.000	0.090 ± 0.000	-0.008 ± 0.000	-0.013 ± 0.000	0.092 ± 0.000	0.207 ± 0.000
AN6V (Add +1.50 D)	3	D05(y)	0.026 ± 0.000	-0.007 ± 0.000	0.027 ± 0.000	0.012 ± 0.000	0.089 ± 0.000	0.003 ± 0.000	-0.002 ± 0.000	0.090 ± 0.000	0.136 ± 0.000
AN6V (Add +1.50 D)	3	D05(−y)	-0.031 ± 0.000	0.005 ± 0.000	0.032 ± 0.000	-0.014 ± 0.000	0.075 ± 0.000	-0.001 ± 0.000	-0.001 ± 0.000	0.077 ± 0.000	0.133 ± 0.000
AN6V (Add +1.50 D)	3	D10(x)	-0.014 ± 0.000	-0.000 ± 0.000	0.014 ± 0.000	0.020 ± 0.000	0.023 ± 0.000	-0.038 ± 0.000	0.007 ± 0.000	0.049 ± 0.000	0.313 ± 0.000
AN6V (Add +1.50 D)	3	D10(y)	-0.002 ± 0.000	0.005 ± 0.000	0.005 ± 0.000	0.008 ± 0.000	0.049 ± 0.000	-0.002 ± 0.000	0.002 ± 0.000	0.050 ± 0.000	0.058 ± 0.000
AN6V (Add +1.50 D)	3	D10(−y)	-0.027 ± 0.000	-0.001 ± 0.000	0.027 ± 0.000	0.015 ± 0.000	-0.014 ± 0.000	-0.003 ± 0.000	0.000 ± 0.000	0.021 ± 0.000	0.064 ± 0.000
AN6V (Add +1.50 D)	4.5	C	-0.040 ± 0.000	-0.007 ± 0.000	0.041 ± 0.000	-0.040 ± 0.000	0.222 ± 0.000	0.004 ± 0.000	-0.002 ± 0.000	0.226 ± 0.000	0.413 ± 0.000
AN6V (Add +1.50 D)	4.5	D05(x)	-0.045 ± 0.000	-0.006 ± 0.000	0.046 ± 0.000	-0.028 ± 0.000	0.200 ± 0.000	-0.065 ± 0.000	-0.009 ± 0.000	0.212 ± 0.000	0.452 ± 0.000
AN6V (Add +1.50 D)	4.5	D05(y)	-0.002 ± 0.000	-0.023 ± 0.000	0.023 ± 0.000	-0.018 ± 0.000	0.261 ± 0.000	-0.000 ± 0.000	-0.002 ± 0.000	0.261 ± 0.000	0.388 ± 0.000
AN6V (Add +1.50 D)	4.5	D05(−y)	-0.085 ± 0.000	0.012 ± 0.000	0.085 ± 0.000	-0.032 ± 0.000	0.144 ± 0.000	-0.002 ± 0.000	0.000 ± 0.000	0.148 ± 0.000	0.347 ± 0.000
AN6V (Add +1.50 D)	4.5	D10(x)	-0.766 ± 0.002	-0.363 ± 0.001	0.848 ± 0.002	-0.105 ± 0.001	-0.037 ± 0.001	-1.244 ± 0.004	-0.710 ± 0.002	1.437 ± 0.005	2.015 ± 0.007
AN6V (Add +1.50 D)	4.5	D10(y)	-0.344 ± 0.001	-0.222 ± 0.001	0.409 ± 0.001	0.398 ± 0.001	0.796 ± 0.001	-0.020 ± 0.000	-0.012 ± 0.000	0.890 ± 0.002	1.133 ± 0.003
AN6V (Add +1.50 D)	4.5	D10(−y)	-1.046 ± 0.002	-0.429 ± 0.001	1.131 ± 0.002	-0.889 ± 0.001	-1.469 ± 0.003	-0.055 ± 0.001	-0.029 ± 0.001	1.719 ± 0.003	2.500 ± 0.005
AN6VM (Add +3.00 D)	3	C	0.023 ± 0.000	-0.028 ± 0.000	0.036 ± 0.000	-0.042 ± 0.000	0.224 ± 0.000	0.007 ± 0.000	-0.002 ± 0.000	0.228 ± 0.000	0.344 ± 0.000
AN6VM (Add +3.00 D)	3	D05(x)	0.001 ± 0.000	-0.000 ± 0.000	0.001 ± 0.000	-0.022 ± 0.000	0.179 ± 0.000	0.015 ± 0.000	-0.027 ± 0.000	0.183 ± 0.000	0.394 ± 0.000
AN6VM (Add +3.00 D)	3	D05(y)	0.062 ± 0.000	-0.013 ± 0.000	0.063 ± 0.000	0.022 ± 0.000	0.158 ± 0.000	0.008 ± 0.000	-0.001 ± 0.000	0.160 ± 0.000	0.251 ± 0.000
AN6VM (Add +3.00 D)	3	D05(−y)	-0.053 ± 0.000	0.010 ± 0.000	0.054 ± 0.000	-0.029 ± 0.000	0.170 ± 0.000	0.002 ± 0.000	0.001 ± 0.000	0.173 ± 0.000	0.278 ± 0.000
AN6VM (Add +3.00 D)	3	D10(x)	-0.031 ± 0.000	0.005 ± 0.000	0.031 ± 0.000	0.041 ± 0.000	0.046 ± 0.000	-0.028 ± 0.000	0.002 ± 0.000	0.067 ± 0.000	0.562 ± 0.000
AN6VM (Add +3.00 D)	3	D10(y)	0.006 ± 0.000	0.009 ± 0.000	0.011 ± 0.000	0.017 ± 0.001	0.060 ± 0.001	0.000 ± 0.000	0.004 ± 0.000	0.062 ± 0.001	0.082 ± 0.000
AN6VM (Add +3.00 D)	3	D10(−y)	-0.052 ± 0.000	-0.003 ± 0.000	0.052 ± 0.000	0.027 ± 0.000	0.004 ± 0.000	-0.000 ± 0.000	0.002 ± 0.000	0.028 ± 0.000	0.133 ± 0.000
AN6VM (Add +3.00 D)	4.5	C	-0.032 ± 0.004	-0.022 ± 0.002	0.039 ± 0.002	-0.080 ± 0.001	0.437 ± 0.003	0.003 ± 0.000	-0.004 ± 0.000	0.444 ± 0.002	0.784 ± 0.000
AN6VM (Add +3.00 D)	4.5	D05(x)	-0.075 ± 0.000	-0.029 ± 0.000	0.080 ± 0.000	-0.069 ± 0.000	0.380 ± 0.000	-0.099 ± 0.000	-0.051 ± 0.000	0.402 ± 0.000	0.821 ± 0.001
AN6VM (Add +3.00 D)	4.5	D05(y)	0.041 ± 0.000	-0.048 ± 0.000	0.063 ± 0.000	-0.035 ± 0.000	0.464 ± 0.000	0.005 ± 0.000	-0.004 ± 0.000	0.465 ± 0.000	0.709 ± 0.000
AN6VM (Add +3.00 D)	4.5	D05(−y)	-0.189 ± 0.002	-0.027 ± 0.002	0.191 ± 0.003	-0.142 ± 0.003	0.240 ± 0.003	-0.003 ± 0.001	-0.004 ± 0.001	0.279 ± 0.001	0.703 ± 0.002
AN6VM (Add +3.00 D)	4.5	D10(x)	-0.913 ± 0.002	-0.310 ± 0.001	0.965 ± 0.002	-0.198 ± 0.001	-0.167 ± 0.001	-1.533 ± 0.004	-0.727 ± 0.002	1.716 ± 0.005	2.390 ± 0.006
AN6VM (Add +3.00 D)	4.5	D10(y)	-0.257 ± 0.001	-0.207 ± 0.000	0.331 ± 0.001	0.377 ± 0.001	0.898 ± 0.001	-0.005 ± 0.001	-0.008 ± 0.000	0.974 ± 0.001	1.174 ± 0.002
AN6VM (Add +3.00 D)	4.5	D10(−y)	-1.473 ± 0.001	-0.330 ± 0.001	1.510 ± 0.001	-0.956 ± 0.001	-2.146 ± 0.002	-0.040 ± 0.002	-0.017 ± 0.001	2.350 ± 0.002	3.259 ± 0.002

Figure 2 shows the primary and secondary spherical aberration coefficients, $Z(4:0)$ and $Z(6:0)$, respectively. Figure 3 depicts the vertical and horizontal coma coefficients, including primary coma, $Z(3:-1)$ and $Z(3:1)$, and secondary coma, $Z(5:-1)$ and $Z(5:1)$. The remaining Zernike polynomials have no significant impact, as the root-mean-square (RMS) values calculated by including all Zernike polynomials up to the 8th order for each IOL are nearly identical to those obtained when only the previously mentioned polynomials are considered. RMS values in microns for spherical aberration, coma and higher-order aberrations (polynomials of orders 3 to 8) are shown in Figure 4.

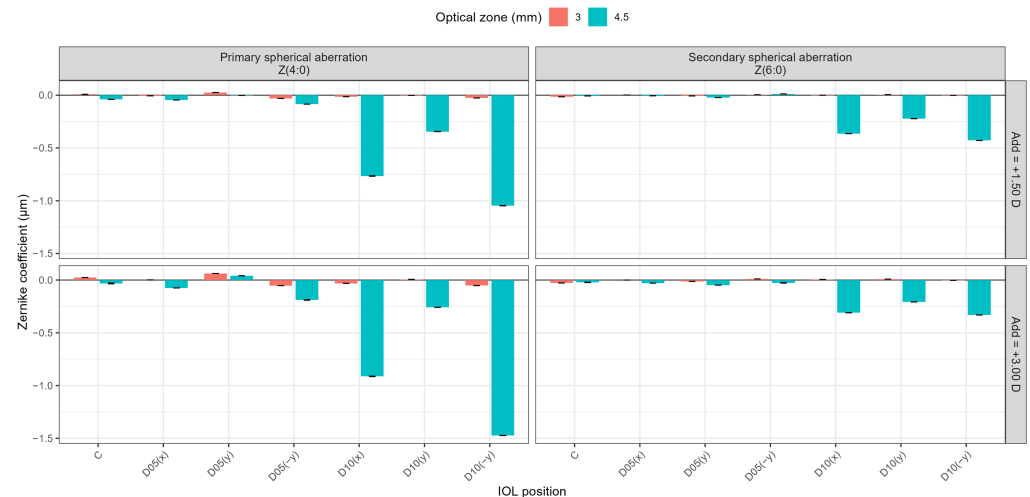


Figure 2. Primary and secondary spherical aberration Zernike coefficients, $Z(4:0)$ and $Z(6:0)$, for 3.0 and 4.5 mm apertures with induced decentration of 0.5 and 1.0 mm at the positions analyzed in the study. C: centered; D05(x): 0.5 mm horizontal decentration toward the +x direction; D10(x): 1.0 mm horizontal decentration toward the +x direction; D05(y): 0.5 mm vertical decentration toward the +y direction; D05(−y): 0.5 mm vertical decentration toward the −y direction; D10(y): 1.0 mm vertical decentration toward the +y direction; D10(−y): 1.0 mm vertical decentration toward the −y direction.

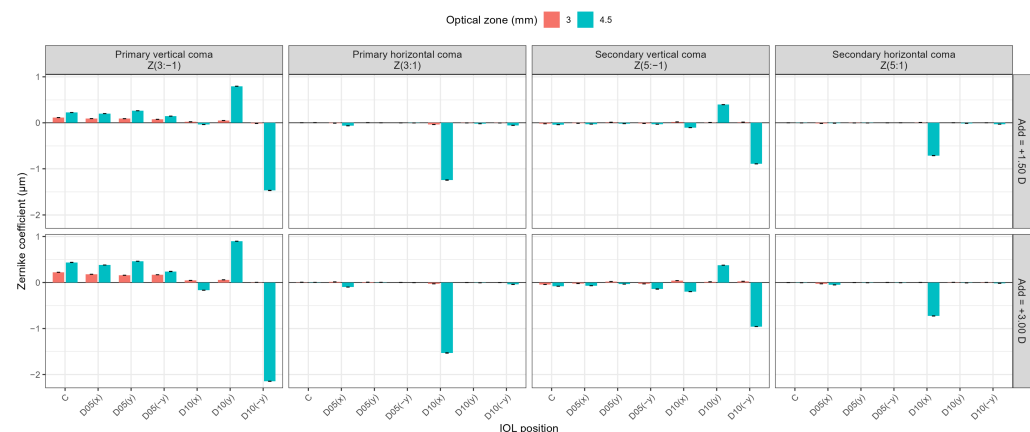


Figure 3. Primary coma, and secondary coma aberration Zernike coefficients, $Z(3:1)$, $Z(3:-1)$, $Z(5:1)$ and $Z(5:-1)$, for 3.0 and 4.5 mm apertures with induced decentration of 0.5 and 1.0 mm at the positions analyzed in the study. C: centered; D05(x): 0.5 mm horizontal decentration toward the +x direction; D10(x): 1.0 mm horizontal decentration toward the +x direction; D05(y): 0.5 mm vertical decentration toward the +y direction; D05(−y): 0.5 mm vertical decentration toward the −y direction; D10(y): 1.0 mm vertical decentration toward the +y direction; D10(−y): 1.0 mm vertical decentration toward the −y direction.

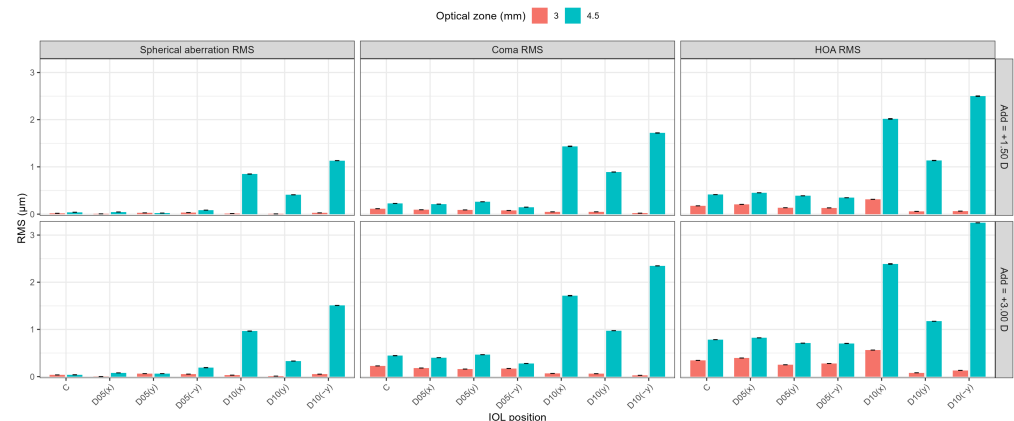


Figure 4. RMS spherical aberration, coma and HOAs (polynomials of orders 3 to 8) of two optical zones (3.0 and 4.5 mm) for both IOL designs. C: centered; D05(x): 0.5 mm horizontal decentration toward the +x direction; D10(x): 1.0 mm horizontal decentration toward the +x direction; D05(y): 0.5 mm vertical decentration toward the +y direction; D05(−y): 0.5 mm vertical decentration toward the −y direction; D10(y): 1.0 mm vertical decentration toward the +y direction; D10(−y): 1.0 mm vertical decentration toward the −y direction.

3.1. Spherical Aberration Changes

As can be seen in Figure 2, primary spherical aberration and secondary spherical aberration remained close to neutrality when both IOL designs were in centered conditions, suggesting a controlled spherical aberration profile, for both optical zones (3.0 mm and 4.5 mm). For the 3.0 mm optical zone, only minimal changes were observed with the induced horizontal and vertical decentrations compared with the centered position. Under this condition, both primary and secondary spherical aberrations remained limited for both IOL designs, with no appreciable differences between superior and inferior vertical displacements. However, when analyzed for a larger aperture (4.5 mm), the impact of decentration became more pronounced for primary spherical aberration, with a greater increase in the Zernike values similar to both IOL designs (from approximately $-0.04 \mu\text{m}$ at centered position to between $-1.05 \mu\text{m}$ (AN6V) and $-1.47 \mu\text{m}$ (AN6VM) at 1.0 mm inferior decentration). By comparison, for secondary spherical aberration, the effect produced by decentration is very slight for both designs compared to that produced in primary spherical aberration.

3.2. Coma Aberration Changes

In Figure 3, we observed clearly differentiated behavior between both aperture conditions. For the smaller aperture (3.0 mm), Zernike values remain close to zero for the primary and secondary coma aberration across all analyzed positions in both IOL designs, which indicate a global stability of the wavefront and a low presence of comatic aberrations. In contrast, for the larger aperture (4.5 mm), 1.0 mm of lens decentration induced marked changes in coma coefficient, mainly in the primary terms ($Z(3;-1)$ reversing in sign and increasing in magnitude from approximately 0.22 to $0.44 \mu\text{m}$ at centered position to $-1.47 \mu\text{m}$ (AN6V) to $-2.15 \mu\text{m}$ (AN6VM) at D10(−y)). A direction-specific pattern was observed: vertical decentration predominantly affected vertical coma, $Z(3;-1)$, whereas horizontal decentration predominantly affected horizontal coma, $Z(3;1)$. Moreover, opposite vertical displacements induced opposite changes in the vertical coma terms, as shown by the positive values for D10(y) and the negative values for D10(−y). Secondary coma terms showed smaller changes with a similar pattern. These values are observed similarly for both low-addition AN6V and high-addition AN6VM.

It can be observed in both Figures 2 and 3 the influence of the direction of vertical decentration. Unlike horizontal decentration, vertical displacement may not produce symmetrical optical behaviors because the power distribution of the segmented refractive IOL is not symmetrical across the distinct refractive regions. Consequently, superior (y) and inferior ($-y$) decentrations interact differently with the optical design. This asymmetry is reflected in the aberration profiles, with inferior decentration inducing larger changes than superior decentration, particularly for the larger aperture, likely because inferior decentration causes the optical axis to intersect a more eccentric region of the asymmetric optical design.

3.3. Root-Mean-Square Changes

Figure 4 illustrates the changes in RMS induced. As can be observed, in both IOL designs, RMS values increased with increasing decentration, although the magnitude of the effect varied among aberration types. Spherical aberration showed a relatively modest increase, whereas coma exhibited the greatest sensitivity to decentration, with RMS rising from approximately 0.23 to 0.44 μm at centered position to 1.72 to 2.35 μm at 1.0 mm inferior decentration (4.5 mm aperture, D10($-y$)), an absolute increase of approximately 1.49–1.91 μm , compared with an absolute increase of approximately 1.09–1.47 μm for spherical aberration RMS over the same range (from 0.04 μm to 1.13–1.51 μm). Consequently, the total higher-order aberrations (HOAs) RMS also increased substantially as decentration progressed. These effects were consistently more pronounced for the 4.5 mm optical zone than for the 3.0 mm aperture, indicating greater optical degradation under larger pupil conditions. Furthermore, the high-addition AN6VM design demonstrated slightly higher aberration levels at larger decentrations compared with the low-addition AN6V.

4. Discussion

When selecting an IOL, surgeons should consider the potential impact of postoperative decentration, particularly in specific conditions such as pseudoexfoliation [22]. Over recent decades, the magnitude of postoperative IOL decentration has decreased considerably, reflecting advances in surgical techniques and lens design. While mean decentration values of approximately 0.64 mm were reported in 1992 [23], more recent studies report averages of 0.2–0.3 mm. Nevertheless, approximately 10% of patients still exhibit clinically relevant decentrations exceeding 0.5 mm [16], which may compromise optical quality, inducing glare, halos, reduced contrast sensitivity and increased higher-order aberrations [24,25]. Premium IOLs are particularly sensitive to decentration, and optical aberrations in any imaging system increase with aperture size [26,27], making the effects of misalignment more pronounced under larger pupil conditions [28,29].

This study presents objective in vitro measurements of the low-addition (AN6V) and high-addition (AN6VM) rotationally asymmetric Acunex IOLs under controlled horizontal and vertical decentration conditions. To our knowledge, this is the first study to specifically investigate the effect of decentration on the AN6V and AN6VM platforms; direction-dependent decentration sensitivity has previously been reported for other segmented, rotationally asymmetric multifocal IOLs [30–33].

Overall, our results demonstrate that the optical performance of both rotationally asymmetric, segmented-refractive Acunex designs deteriorates progressively as decentration increases, an effect that becomes considerably more pronounced at the larger 4.5 mm aperture. Both IOLs tolerated small decentrations reasonably well, whereas larger displacements (1.0 mm) induced a substantial increase in higher-order aberrations, primarily coma. Importantly, the resulting aberration pattern depended not only on the magnitude of decentration but also on its direction, reflecting the intrinsically asymmetric optical

profile of these lenses. From a theoretical standpoint, lateral displacement of an optical element preferentially couples into odd-order, asymmetric aberrations such as coma, with a comparatively smaller effect on spherical aberration [34]. This principle is consistent with our finding that coma, rather than spherical aberration, was the dominant aberration induced by decentration in both IOL models.

Primary spherical aberration remained relatively stable for the small aperture (3.0 mm) but increased progressively under the larger aperture (4.5 mm) as decentration increased, showing a shift toward negative values. This behavior was highly consistent between both designs, suggesting a similar sensitivity to decentration. A clear dependence on the direction of vertical displacement was also observed for primary spherical aberration, with inferior decentration producing more pronounced changes than superior decentration, especially in the high-addition design, whereas secondary spherical aberration remained comparatively unaffected, with Zernike values not exceeding $0.5\ \mu\text{m}$ for 1.0 mm decentration. This asymmetric behavior is consistent with the vertically asymmetric geometry of segmented refractive IOLs, in which inferior displacement causes the optical axis to intersect a more eccentric region of the design. This pattern parallels reports for other aspheric platforms, in which IOLs incorporating substantial negative spherical aberration to compensate corneal positive spherical aberration are particularly susceptible to decentration-induced aberration changes, whereas aberration-free designs remain comparatively stable [15]. Clinically, the decentration-induced shift toward negative spherical aberration observed in this study should not be considered advantageous. Although an intentionally targeted amount of negative spherical aberration may partially compensate for positive corneal spherical aberration and extend depth of focus, an uncontrolled aberration shift caused by IOL decentration may degrade retinal image quality and reduce, rather than enhance, functional depth of focus. This effect was more evident for the larger aperture, suggesting greater clinical relevance under mesopic conditions, when a larger pupil allows more peripheral rays to reach the retina [35].

Primary coma was the dominant contributor, with similar induced values for both the low- and high-addition IOLs, and inferior vertical decentration produced the highest levels of induced vertical coma, whereas horizontal coma was mainly induced by horizontal decentration. This marked directional asymmetry is a direct consequence of the segmented, non-rotationally symmetric architecture of the Acunex platform, whose eccentric notch and near addition sector break the rotational symmetry assumed for centered IOLs. A comparable orientation-dependent behavior, in which the specific meridian of displacement, rather than its magnitude alone, determines whether optical quality improves or deteriorates at a given focus, has been described for other rotationally asymmetric refractive multifocal IOLs [36]. This directional sensitivity constitutes a defining optical signature of segmented multifocal designs and carries direct surgical relevance, since a vertical postoperative shift in identical magnitude may produce markedly different visual outcomes depending on whether it occurs toward or away from the near segment. Clinically, the resulting increase in vertical and horizontal coma is particularly relevant because this asymmetric, higher-order blur cannot be corrected with conventional spectacle lenses. Elevated coma has been associated with reduced contrast sensitivity, decreased visual acuity under mesopic conditions, and an increased perception of photic phenomena such as glare and halos, all of which may negatively affect patient satisfaction after cataract surgery [37,38].

Overall, our findings are consistent with previous optical bench studies of rotationally asymmetric refractive IOLs. Baur et al. [30] and Oshika et al. [31] similarly reported that increasing decentration mainly induces coma and astigmatism, with larger aperture amplifying optical degradation, in the Lentis Comfort IOL (Oculentis GmbH, Berlin, Germany), a lens that shares the same segmented optical concept analyzed in the present

study, differing mainly in material (hydrophilic vs. the hydrophobic Acunex platform). Liu et al. [32], evaluating the SBL-3 IOL, a rotationally asymmetric refractive multifocal design with an inferior near segment conceptually analogous to the Acunex lens, likewise found that optical quality was highly sensitive to both the magnitude and orientation of decentration, with opposite effects on near and distance foci depending on whether displacement occurred toward or away from the near zone. Notably, the clinical relevance of even the minor malposition in this IOL class has already been documented in vivo: a near-segment decentration of only 0.2 mm has been reported to induce a myopic shift with symptomatic blurred vision, and displacement toward the distance zone has been associated with reduced near visual [32]. These reported magnitudes are considerably smaller than the 0.5–1.0 mm decentrations evaluated in the present study, underscoring that segmented refractive multifocal platforms as a class may become symptomatic at submillimetric displacements. Considered together with the postoperative decentration distributions reported earlier, in which approximately 10% of eyes exceed 0.5 mm of decentration [16], the present findings indicate that the 0.5 mm condition evaluated here corresponds to a realistic, clinically relevant scenario for a meaningful minority of patients, whereas the 1.0 mm condition represents a more extreme, though clinically documented, degree of malposition. Given that segmented refractive platforms as a class can become symptomatic at decentrations as small as 0.2 mm [32], which is smaller than the lowest magnitude evaluated in the present study, the present findings should be interpreted within the range of decentrations investigated and do not exclude clinically relevant optical changes at smaller displacements. The FEMTIS Comfort IOL, a biconvex refractive multifocal lens with a sector-shaped, rotationally asymmetric +1.50 D addition segment conceptually and dioptrically analogous to the AN6V, showed minimal sensitivity to horizontal decentration but noticeable changes with vertical decentration, particularly under photopic conditions [39]. This direction-dependent pattern parallels our own finding of markedly greater sensitivity to vertical than horizontal decentration, and reinforces that rotational asymmetry, rather than addition power alone, is the primary driver of direction-dependent decentration sensitivity in this class of lenses. In contrast, the MiniWELL IOL, a rotationally symmetric EDoF design based on three concentric optical zones rather than a segmented sector, showed only minor MTF variation (± 0.06) under ± 0.5 mm decentration at both the 3.0 and 4.5 mm apertures [40]. This contrast between a rotationally asymmetric, segmented design (FEMTIS Comfort, and by extension Acunex, Lentis Comfort, and SBL-3) and a rotationally symmetric, concentric-zone design (MiniWELL) illustrates that decentration sensitivity in this IOL category is primarily a consequence of rotational asymmetry itself, rather than of a specific addition power or material. A similar steep decentration sensitivity has been reported for other non-rotationally symmetric aspheric multifocal IOLs, with significant reductions in modulation transfer function already at 0.2–0.4 mm of decentration, in contrast to concentric refractive–diffractive designs, which remained comparatively stable over the same range [33]. Viewed against this backdrop, the fact that both Acunex models in the present study maintained close to neutral, stable aberrometric profiles at the smaller 3.0 mm aperture across all tested decentrations, and showed only limited change at 0.5 mm even under the larger 4.5 mm aperture, suggests a comparatively favorable small decentration tolerance among segmented, rotationally asymmetric refractive designs, with clinically meaningful optical degradation confined mainly to the largest displacement (1.0 mm) evaluated under mesopic-equivalent aperture conditions.

Coma exhibited the greatest sensitivity to decentration among the higher-order aberrations evaluated, with a pronounced rise at the larger displacement (1.0 mm), whereas spherical aberration, although also increased at larger aperture, contributed comparatively less to the overall RMS. Total HOA RMS increased substantially with increasing decentra-

tration and was consistently more pronounced at the 4.5 mm aperture, confirming that larger pupil diameters exacerbate the optical impact of IOL decentration, as peripheral rays contribute increasingly to image formation. The high-addition AN6VM design consistently showed slightly higher RMS values than the low-addition AN6V at larger decentrations, suggesting a marginally lower tolerance to positional misalignment. This is in line with previous evidence that higher-addition segmented and diffractive designs, which introduce a more complex distribution of optical power across the pupil, tend to show greater sensitivity to malposition than lower-addition or monofocal counterparts [15].

From a clinical standpoint, these findings translate into several practical considerations for surgeons using the Acunex platform. First, because the eccentric, inferiorly positioned notch is intrinsic to this optical design, achieving adequate alignment between the notch, the capsulorhexis, and the pupil center should be regarded as a specific surgical objective for this lens family, in a manner conceptually similar to axis alignment for toric IOLs. Second, the pronounced aperture-dependence of the induced aberrations indicates that patients with larger mesopic pupils are at greater risk of experiencing coma-driven dysphotopsia (glare, halos, or monocular diplopia) should postoperative decentration occur [24,25], and preoperative mesopic pupil size could reasonably be considered when evaluating candidacy for this IOL family, as has been proposed for other multifocal platforms [38]. Third, careful preoperative identification of eyes at elevated risk of decentration, including pseudoexfoliation, ocular trauma, connective tissue disorders such as Marfan syndrome, weak zonular support, or a history of vitrectomy, is particularly relevant when a segmented refractive design is being considered, given the class-wide directional sensitivity demonstrated here and in other segmented multifocal IOLs [32,33]. Finally, the slightly greater aberrometric sensitivity observed for the high-addition AN6VM relative to the low-addition AN6V suggests that, in patients judged to be at higher risk of postoperative malposition, the lower-addition design may offer a modest optical safety margin, an observation that warrants confirmation in clinical cohorts with measured postoperative decentration. Taken together, these results support incorporating decentration risk into preoperative counseling and lens selection for patients considering rotationally asymmetric multifocal IOLs, in particular regarding expectations for low light visual performance.

Several limitations of the present study should be acknowledged. A limitation of the present study is related to the use of Zernike polynomial decomposition for the characterization of optical designs with discontinuous wavefront profiles. As previously described [17,41], Zernike expansions are inherently better suited for continuous wavefronts, whereas abrupt phase transitions between optical zones may lead to fitting inaccuracies, particularly at the boundaries between regions with different optical power. Consequently, the interpretation of individual aberration terms in discontinuous optical designs may not be as straightforward as in monofocal designs. The expected bias associated with fitting a continuous Zernike polynomial basis to a wavefront with an abrupt phase discontinuity at the sector boundary is concentrated near that transition, and is expected to preferentially inflate higher-order terms (secondary coma, secondary spherical aberration) rather than the dominant primary terms $Z(3:1)$, $Z(3:-1)$, and $Z(4:0)$ that drive the main conclusions of this study. Furthermore, all comparisons presented here are relative, centered vs. decentered, and low vs. high addition, rather than based on absolute coefficient magnitude, which mitigates the practical impact of this fitting bias on the study's conclusions. Nevertheless, despite these methodological limitations, analysis based on Zernike polynomials remains clinically valuable, as it enables quantitative comparison between different intraocular lenses designs and facilitates correlation between in vitro optical measurements and postoperative ocular aberrations. Additionally, the present analysis was deliberately scoped to Zernike/RMS wavefront decomposition, for direct comparability with the companion

centered-position characterization of this platform, and did not include evaluation of the modulation transfer function (MTF), point spread function (PSF), or Strehl ratio. Zernike decomposition allowed the specific aberration mode (primary vs. secondary coma, primary vs. secondary spherical aberration) responsible for the observed degradation to be isolated, information that a single scalar metric such as the Strehl ratio would not by itself disentangle. Nevertheless, MTF/PSF evaluation would provide complementary, more directly image quality-oriented information, and constitutes the natural next step for this platform. Furthermore, the present optical bench analysis was intentionally limited to isolated lateral decentration without IOL tilt or a model cornea, allowing the intrinsic optical response of the IOL to translational misalignment to be characterized independently of confounding factors. Consequently, these findings should be interpreted as describing the optical behavior of the IOL itself rather than the complete in vivo optical system. Future studies incorporating model-eye configurations and combined tilt-decentration conditions will help establish the clinical relevance of these interactions. Another limitation of this study is the inability to perform a direct comparison with previous works, as there are currently no published studies analyzing the effect of decentration on the aberrometric profiles of these two designs (AN6V and AN6VM) of intraocular lenses.

5. Conclusions

Under centered conditions, both intraocular lenses exhibited similar aberrometric profiles, maintaining consistent optical performance even with the larger aperture. However, as decentration increased, particularly with the larger aperture (4.5 mm), a direction-dependent behavior in optical performance became evident, with coma emerging as the aberration most consistently affected.

The changes induced followed patterns that varied in magnitude and direction of decentration. Asymmetric aberrations, especially coma, were the most affected, although primary spherical aberration also showed variations under specific displacement conditions. Although both intraocular lenses displayed similar trends, differences in their responses were observed, suggesting that the addition may influence decentration tolerance, with the high-addition design being the most affected.

These findings indicate that larger magnitudes of decentration produce direction-dependent changes in the aberrometric profile of rotationally asymmetric Acunex intraocular lenses, in particular under larger, mesopic-equivalent aperture conditions. From a clinical standpoint, these results underscore the importance of accurate notch-pupil alignment during implantation of this IOL family and support taking decentration risk factors, and potentially the addition power selected, into account when counseling patients and planning surgery, particularly for those with anticipated large mesopic pupils or predisposing conditions for postoperative malposition.

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Abbreviations

The following abbreviations are used in this manuscript:

IOL(s)	Intraocular lens(es)
EDoF	Extended depth of focus
RMS	Root-mean-square
HOAs	Higher-order aberrations

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