Ophthalmic Research

Research Article

Ophthalmic Res 2023;0:1–10
DOI: 10.1159/000528504

Received: July 26, 2022
Accepted: November 28, 2022
Published online: February ■■■, 2023

Optical Quality Variation of Different Intraocular Lens Designs in a Model Eye: Lens Placed Correctly and in an Upside-Down Position

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Keywords
Intraocular lens flip · Upside-down position · Optical quality

Abstract
Introduction: Intraocular lenses (IOLs) may lose their optical quality if they are not correctly placed inside the capsular bag once implanted. One possible malpositioning of the IOL could be the implantation in an upside-down position. In this work, three aspheric IOLs with different spherical aberration (SA) have been designed and numerically tested to analyse the optical quality variation with the IOL flip, and misalignments, using a theoretical model eye. ***Methods:*** Using the commercial optical design software OSLO, the effect of decentration and tilt was evaluated by numerical ray tracing in two conditions: in their designed position and flipped with respect to the planned position (IOL is implanted upside down). The theoretical model eye used was the Atchison model eye. Seven IOL designs of +27.00 diopters were used: a lens with negative SA to correct the corneal SA, a lens to partially correct the corneal SA, and a lens to not add any SA to the cornea (aberration-free IOL). These lenses were designed with the aspherical surface located on the anterior and posterior IOL surface. A lens with no aspherical surfaces was also included. For the optical quality analysis, the modulation transfer function (MTF) was used, together with the Zernike wavefront aberration coefficients of defocus, astigmatism, and primary coma. ***Results:*** Off-centring and tilting the IOL reduced overall MTF values and increased wavefront aberration errors. With the IOL correctly positioned within the capsular bag, an aberration-free IOL is the best choice for maintaining optical quality. When the IOL is flipped inside the capsular bag, the optical quality changes, with the aberration-free IOL and the IOL without aspheric surfaces providing the worst results. With the lens in an upside-down position, an IOL design to partially correct corneal SA shows the best optical quality results in decentration and tilt, in terms of MTF and wavefront aberrations. ***Conclusion:*** The aberration-free IOL is the best choice when minimal postoperative errors of decentration or tilt are predicted. With IOL flip, the negative SA lens design is the best choice, regarding the root mean square wavefront aberrations. However, in a proper IOL implantation, the IOL designed to partially compensate the corneal SA including asphericity on its posterior surface is the better possible option, even in the presence of decentration or tilt.

Introduction

Cataract surgery is nowadays the most performed surgery around the globe. Through this surgery, between 19 and 20 million patients improve vision annually worldwide [1, 2]. It is considered a safe, effective, and fast method to correct vision in patients with cataracts as it is

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an ambulatory surgery in most cases [3]. The intraocular lens (IOL) used to replace the opacified crystalline lens is the key point to reach all these achievements, together with a satisfactory postoperative vision. Thanks to new IOL materials which make lens folding possible, nowadays the procedure is minimally invasive [4, 5]. This means a rapid healing process for the patients. Prior to surgery, it is necessary to follow some biometrical measurements in order to calculate the IOL power: axial length, corneal keratometry, anterior chamber depth, among others. These measurements should be taken accurately to avoid postoperative refractive error caused by a wrong IOL power selection [6, 7].

Even if cataract surgery is safe, it is not exempt from complications that entail different consequences. Before surgery, as explained before, the most relevant complication is the wrong IOL power selection due to inaccurate preoperative biometrical measurements [6, 7]. Erroneous selection of the IOL overall diameter may be another complication as it must fit the capsular bag size. This measurement is predictable with a white-to-white measurement [8], but a reliable measuring device is not yet available [9].

During surgery, some of the serious complications reported are endophthalmitis, massive haemorrhages, incision burning, and posterior capsular breakage [10]. Haptics breakage [11], IOL rotation (especially relevant in toric IOLs) [12, 13], IOL decentration [14], and the IOL implantation in an upside-down position [15] may be considered less critical complications but still with a relevant impact. The latter is an uncommon complication [15] but not rare considering that the vast majority of IOLs in the market are preloaded, being the lens folding a crucial step.

Postoperatively, a frequent complication with possible optical consequences is the IOL misplacement. IOL misplacement can occur as axial and/or transversal displacement relative to a nominal position or as tilted or rotated position errors relative to a reference plane defined transversal to the optical axis of the eye [16]. From a paraxial optical perspective, axial position errors are known to cause hyperopic or myopic errors, depending on whether the IOL has been placed, respectively, deeper or shallower intended position [17]. From a non-paraxial optical perspective, it is also expected that IOL tilting and decentring may cause a decrease in optical quality due to increased low- (defocus and astigmatism) and high-order wavefront aberrations (coma and spherical aberration [SA]). Higher order aberrations cannot be compensated for by ordinary spectacles or contact lenses and may lead to imminent deterioration of the patient's visual acuity and contrast sensitivity [18, 19]. In these cases, the vision is restored with the IOL repositioning, explantation, or flipping using the technique known as "IOL flip" [15] to correctly place an upside-down lens.

Different optical IOLs designs are available on the market. The SA control has become an important factor to consider when selecting an IOL for a specific patient in relation to corneal SA. Conventional aspheric IOLs have included a negative SA to compensate for the average positive SA of the human cornea, which is reported to be + 0.27 ± 0.02 μm [20]. Other designs partially compensate for the corneal SA through aspheric surfaces, leaving a slightly positive total ocular SA [20–22]. Recently, a large number of IOLs include an aberration-free design so as not to modify the corneal SA. The main advantage of this design is that the optical quality is less affected in cases of misalignment errors, especially decentration, for corneas with different amounts of corneal SA when compared to negative SA IOLs [23–25]. Depending on the manufacturer, the aspheric surface (which provides the IOL's SA) is located on the anterior surface of the IOL, on the posterior surface, or on both. As the IOL optical design is optimized in a concrete position inside the capsular bag, it has always been a challenge to understand what happens when the IOL is implanted in an upside-down position.

To our knowledge, there is no previous published clinical or experimental studies that analyse the consequences of a flipped IOL for optical quality in terms of the modulation transfer function (MTF) and root mean square (RMS) of different aberrations. A flipped IOL is understood as an upside-down position: instead of placing the IOL's anterior surface on the front side of the capsular bag, it is collocated on the back side. Therefore, the aim of this paper is to numerically analyse the behaviour of the optical quality in a pseudophakic model eye when an IOL is implanted upside down from its designed position. For this purpose, aspheric IOLs with different amounts of SA have been designed and the effect of IOL decentration and tilt on image quality has been evaluated for all the IOLs under consideration.

Materials and Methods

Eye Model

To design the aspheric IOLs and evaluate how the optical quality is affected by decentration and tilt, a numerical model of a pseudophakic eye has been implemented with a commercial optical design software: OSLO 2022 EDU Edition, 22.1 (Lambda Research Corporation). The eye model was based on Atchison's schematic eye [26] in which the lens has been replaced by the different designed IOLs. The cornea, pupil, and retina data have

Table 1. Eye model and parameters used for IOLs designs and simulations

Surface	Radius, mm	Thickness, mm	Refractive index, at 555 nm	Asphericity (Q)
Anterior cornea	7.77	0.55	1.376	−0.150
Posterior cornea	6.40	2.72	1.337	−0.275
Pupil	Infinite	1.78	1.337	–
IOL anterior surface	5.55	0.90	1.460	To be determined according to IOL design
IOL posterior surface	−25.30	To be determined according to IOL position*	1.336	To be determined according to IOL design
Retina	−12.82			0.260

*Distance between IOL posterior vertex and retina is 17.37 mm for the IOLs in natural position and 17.63 mm for IOLs in an upside-down position.

been used from the Atchison model eye without any variation (see Table 1 for details). The eye model cornea presents a fourth-order Zernike (Z_4^0) standard ANSI (the abbreviation of American National Standard Institute) SA of +0.242 μm for a 6.00 mm entrance pupil diameter (corresponding to a 5.45 mm iris size) and a refractive power of +42.48 D. The position of the iris was 2.72 mm from the posterior corneal apex and the on-axis position of the IOL within the pseudophakic eye model was set at 4.5 mm (posterior corneal vertex to IOL anterior surface vertex), according to an effective lens position in pseudophakic eyes [27]. For each corresponding IOL design, the depth of the vitreous chamber was set in order to get the paraxial image on the retina.

IOL Design

The IOLs models were designed with a refractive power of +27.00 D, using the data of the semi-finished IOL material from Benz Research & Development Corp corresponding with a product which is available in the European IOL market. It was a hydrophilic material with a refractive index of n = 1.460 at a wavelength of λ = 546 nm, where one of the surface radius was previously determined by the manufacturer, with the radius of curvature for the posterior surface being −25.3 mm for all lenses. Two concepts of aspherical IOLs were designed, placing the asphericity on the anterior and posterior surface of the lens. For comparison, spherical IOLs with the same dioptric power and radius of curvature were designed and evaluated. The shape factor of all lenses was +0.64 and is calculated as $\left(R_{\text{posterior radius}} + R_{\text{anterior radius}}\right)/\left(R_{\text{posterior radius}} - R_{\text{anterior radius}}\right)$.

For each aspheric IOL concept (with the asphericity in the anterior and posterior surface of the lens), three types of aspheric lenses were designed: lens A was an IOL with negative fourth-order Zernike SA (Z_4^0) to totally compensate for the positive SA (Z_4^0) of the Atchison cornea. Lens B was designed with an amount of SA that partially corrects the positive fourth-order Zernike's SA of the Atchinson's cornea, leaving the eye with positive SA. Lens C is an IOL that does not add any fourth-order Zernike SA (Z_4^0) to the eye, taking into account the convergent light beam that comes from the cornea. The fourth-order Zernike coefficient (Z_4^0) was expressed according to the American National Standards Institute Z80.28–2017 [28]. All lenses' data are collected in Table 2, where the SA aberration of the lenses for an entrance pupil diameter of 6.00 mm is also shown. To perform the optimization, a commercial optical design software (OSLO) was used and the fourth-order Zernike SA was utilized to determine the appropriate asphericity. The aspheric surface used to model the different IOLs takes the form of a rotationally symmetric conical cross-section with the sagitta defined as follows:

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1 + Q)c^2r^2}} \tag{1}$$

where z is the sagitta, r is the radial coordinate surface, c is the curvature of the vertex, and Q is the asphericity. For $-1 < k < 0$, the curvature is increasingly flatter at the periphery, $k = 0$ is a sphere, and when $k > 0$ the curvature becomes steeper at the periphery.

Numerical Simulations

Once all the IOLs were designed (see details in Table 2), their optical performance was evaluated using the aforementioned optical design software (OSLO) for different decentration and tilt conditions in the Atchison model eye [26]. Simulations have been performed for the three designed IOLs: (1) the lens aspherical surface was placed on the anterior surface of the lens, (2) the lens aspherical surface was placed on the posterior surface of the lens, and (3) the spherical IOL. In addition, another condition has been considered: lens designed with aspheric anterior surface but placed upside down (the aspherical surface is now located posteriorly) in the eye model. In this position, the shape factor was −0.64 and the SA for a 6 mm entrance pupil is −0.214 μm for lens A, −0.205 μm for lens B, −0.197 μm for lens C, and −0.188 μm for the spherical lens.

Firstly, each IOL was decentred from 0.00 mm (on-axis position) to 1.00 mm, in steps of 0.25 mm. Secondly, the optical axis of the IOL was tilted from 0.00 degrees (corneal optical axis aligned with the IOL optical centre) to 5.00 degrees, in 1.00 degree steps. When tilting the lenses, the optical vertex always coincided with the pupil axis of the model eye. For each decentration and tilt, the tangential and sagittal MTF was calculated at 100 cycles/mm for a 3.00 mm pupil diameter following the standard ISO 11979-2 [29]. As well as the MTF, Zernike wavefront aberration coefficients associated with defocus (Z_2^0), astigmatism (Z_2^{-2}, Z_2^2), and primary coma (Z_3^{-1}, Z_3^1) were calculated for a wavelength of 546 nm and

Table 2. Parameters of IOL used in the simulations

IOL refractive power (D)	Radius (mm)		Centre thickness, mm	IOL design	Asphericity (Q)		IOL SA (µm) Ø6 mm entrance pupil	Shape factor
	anterior surface	posterior surface			anterior surface	posterior surface		
+27.00	5.55	−25.30	0.90	Lens A	−1.5491	0	−0.242	+0.64
				Lens A post-asph	0	−170.0	−0.242	
				Lens B	−0.992	0	−0.121	
				Lens B post-asph	0	−122.0	−0.121	
				Lens C	−0.524	0	0.000	
				Lens C post-asph	0	−61.0	0.000	
				Spherical	0	0	+0.151	

Q represents the asphericity values and SA represents the spherical aberration of IOL for 6.00 mm pupil diameter.

3.00 mm pupil diameter. The RMS was calculated as Z_2^0 and the square root of the sum (Z_2^{-2}, Z_2^2) or (Z_3^{-1}, Z_3^1) squared for defocus, astigmatism, and primary coma, respectively.

Results

Figure 1 (left column, white background) shows the MTF variation with decentration and Figure 1 (right column, grey background) shows the MTF variation with tilt. The MTF values were measured at 100 cycles/mm with a 3.00 mm diameter pupil following the procedure described in the ISO 11979-2 [29]. Each row shows the MTF for every IOL design and position: (a) IOL with asphericity on the anterior surface, correctly placed in the design position. (b) IOL was placed upside down from its design position. (c) IOL with aspheric surface on the posterior face, correctly positioned in the design position. The lens with no aspheric surfaces (spherical IOL) has obviously not been included in Figure 1c.

Regarding on-axis MTF, lens A had the highest MTF values when correctly placed in its design position (see Fig. 1, rows a and c), as it is an aberration-correcting IOL for that cornea, while the lowest MTF value was obtained for the spherical lens. Lenses B and C, in that order, had lower values than lens A. This was expected due to their designs: partial aberration correction and neutral aberration IOLs, respectively. Although when it comes to upside-down lens position, all lens designs worsened their optical quality, obtaining MTF values always lower than 0.30 (see Fig. 1, row b).

However, when the IOL was decentred, the amount of MTF degradation was highly dependent on the IOL design. The MTF value of lens A (see Fig. 1, white background, rows a and c) decays rapidly with decentration. Lens B, lens C, and the spherical lens were barely sensitive to decentration.

Figure 1 (grey background) shows the MTF as a function of tilt. In this case, MTF was less sensitive to IOL design than to IOL decentration. For well-positioned IOLs (both anterior and posterior aspheric surfaces, Fig. 1, rows a and c), all lenses provided a nearly constant MTF over a range of 2-degree tilt. From 3-degree tilt onwards, MTF values progressively decayed for all lenses, especially for tangential MTF. When the lenses were flipped (see Fig. 1, white background, row b), all lenses returned to MTF values below 0.3.

From the Zernike wavefront aberration coefficients associated with defocus (Z_2^0), astigmatism (Z_2^{-2} and Z_2^2), and primary coma (Z_3^{-1} and Z_3^1), RMS was calculated for a pupil diameter of 3.00 mm for all designed IOLs. Figures 2–4 show the results of defocus, astigmatism, and coma RMS, respectively. In general, IOL decentration and tilt increased wavefront aberrations regardless of IOL design, with the aberration value being higher when decentration was applied compared to tilt. As expected, without decentration and tilt, the RMS astigmatism and coma are zero. Figure 2 shows that the lens C and the spherical IOL induce the highest RMS defocus value for on-axis position. However, when decentration was applied, lens A obtained higher defocus values. As for the flipped IOLs (row b), all lenses maintained their behaviour for the on-axis defocus value but increased considerably. Lenses with

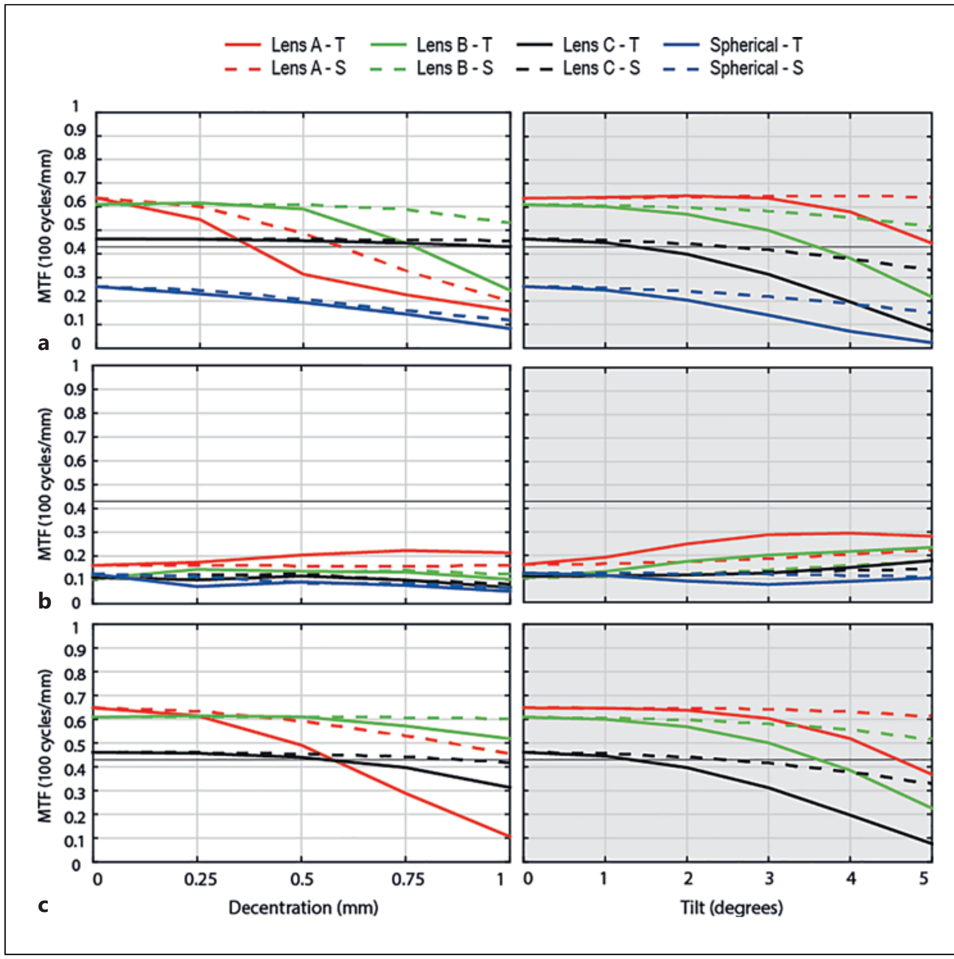

Fig. 1. On-axis MTF of the designed IOLs as a function of decentration (white background) and tilt (grey background) with a 3.00 mm pupil diameter and 100 cycles/mm. The tangential MTF (continuous lines) and the sagittal MTF (dashed lines) are shown for each condition: aspherical anterior surface IOL on its design position (**a**), aspherical anterior surface IOL placed upside down (**b**), and aspherical posterior surface IOL on its design position (**c**).

asphericity on their posterior surface to compensate for corneal SA (row c) presented better defocus results for both on-axis and misalignment, showing only slight increases in defocus. These results are repetitive for astigmatism and coma aberration (Fig. 3, 4). It is visible how the lenses behave when decentration is highly variable depending on the IOL design. On the contrary, the effect of tilt on RMS defocus, astigmatism, and coma were less influenced by the IOL design.

Lenses flipped upside down demonstrated the worst quality. Lens A presented the lowest quality among the anterior aspheric surface lenses for both astigmatism and coma, while the spherical IOL presented the worst values in the flipped lens position, this value being the highest.

Conclusion

Fortunately, the inadvertent implantation of an IOL in an upside-down position is not a common complication. Some publications written as case reports explain the possible complications related to inverted IOL implantation. These are capsular block syndrome [30], and consequently glaucoma [31], posterior capsule opacification, as a consequence of the lack of a 360 degrees square edge on the anterior surface of the IOL [15], and refractive error due to the incorrect lens placement [30]. Haptic design is a critical factor in axial misplacement of the flipped IOL. Inverting the optic also reverses the haptic angulation, so the lens will be displaced towards the cornea [30]. However, nowadays the market trend is

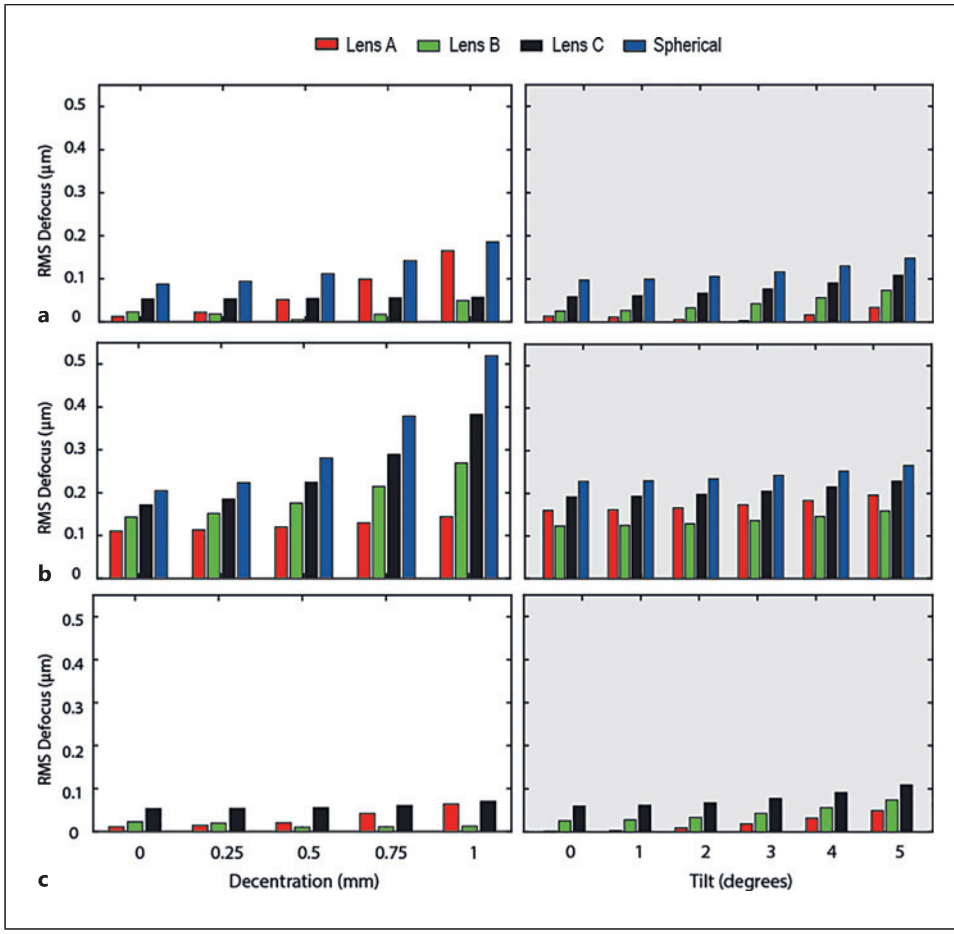

Fig. 2. RMS defocus (Z_2^0) values of the designed IOLs for decentration (white background) and tilt (grey background) with each different lens design or condition: aspherical anterior surface IOL on its design position (**a**), aspherical anterior surface IOL placed upside down (**b**), and aspherical posterior surface IOL on its design position (**c**).

to design IOLs with no haptic angulation, and even with an axially displaced IOL the refractive error can be easily compensated with any kind of refractive correction. Some authors have described different techniques to flip an IOL which has been implanted in the upside-down position [32, 33], but the minor consequences that a wrong implanted IOL produces in patients lead to implementing conservative management during surgery, leaving the IOL flipped [30].

Following these premises, no previous studies have been published showing the optical consequences of implanting an inverted IOL with respect to the designed position. In this article, we numerically analysed the consequences on the optical quality when a flipped IOL is decentred and tilted compared to correctly implanted IOLs. Furthermore, as the IOL designs include the asphericity on the anterior surface, the numerical analysis of optical quality with decentration and tilt has also been analysed with aspheric posterior surface IOL designs, correctly positioned within the model eye.

Regarding the MTF values provided by the IOLs on their design position (Fig. 1a), as expected, the lens fully compensating for corneal SA (lens A) and the lens partially compensating for corneal SA (lens B) obtained the highest on-axis value, but this decreased rapidly with the lens decentration. The lens with aberration-free design (lens C) maintained the on-axis MTF value obtained better, while the spherical lens (with no aspheric surface) never reached an MTF value higher than 0.43. In previous studies, we used the Navarro model eye to analyse the behaviour of optical quality, finding similar results in which the aberration-free lens maintained better its optical quality [24] with decentration and tilt as well as producing extreme SA values through the corneal

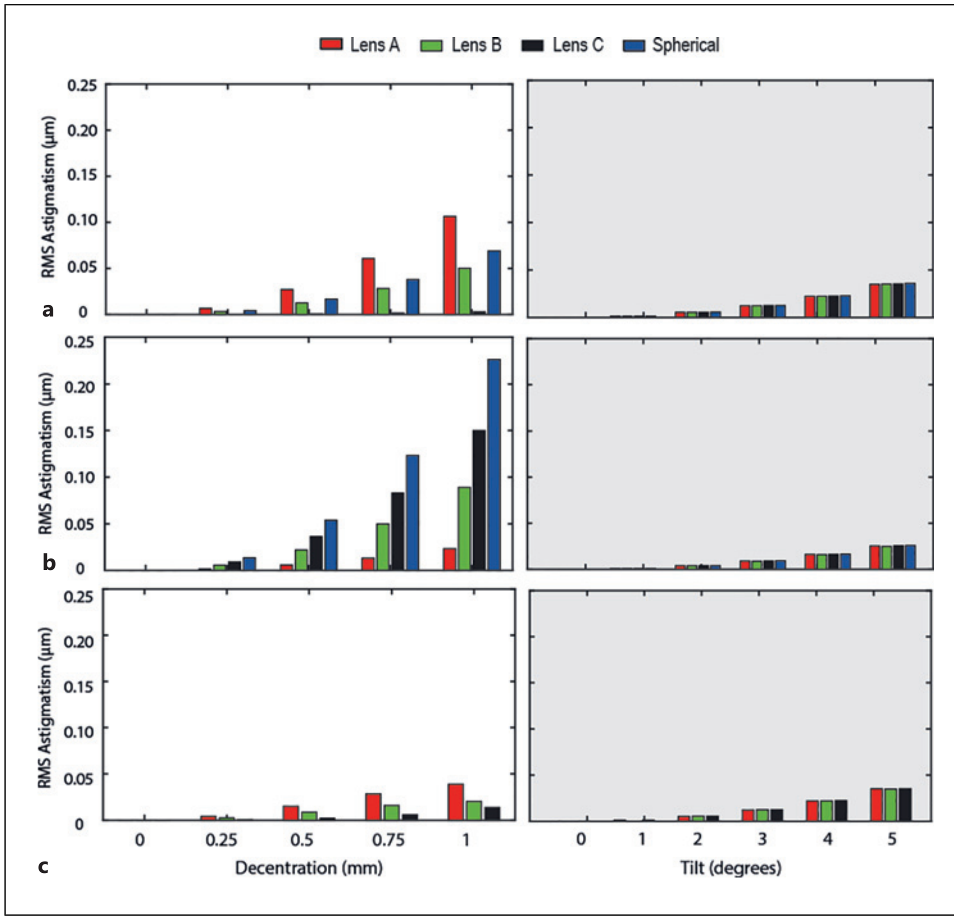

Fig. 3. RMS astigmatism (Z_2^{-2} and Z_2^2) values of the designed IOLs for decentration (white background) and tilt (grey background) with each different lens design or condition: aspherical anterior surface IOL on its design position (**a**), aspherical anterior surface IOL placed upside down (**b**), and aspherical posterior surface IOL on its design position (**c**).

asphericity [25]. With all IOLs flipped (Fig. 1), all lenses suffered a sharp drop in optical quality with MTF values under 0.20 for decentration and tilt as they strongly increase their SA when flipped (SA for a 6 mm entrance pupil is −0.214 μm for lens A, −0.205 μm for lens B, −0.197 μm for lens C, and −0.188 μm for the spherical lens). In the case of the lenses with aspherical posterior surface design and well positioned inside the model eye (Fig. 1c), the results obtained were similar to the original designs in both decentration and tilt.

The defocus values showed that lenses B and C obtained the best results when decentration was applied (Fig. 2a), while lens A produced better optical quality with tilt, those cases with the lens in its design position. With the lenses flipped from their design position (Fig. 2b), the lens that fully compensates for the SA of the model eye (lens A) showed the best result, especially for decentration. In this scenario, the lens which partially compensates corneal SA and the lens that does not add any SA to the cornea suffered an increase in the RMS defocus. Analysing the lenses designed with a posterior aspheric surface and properly positioned inside the model eye (Fig. 2c), all IOLs improve the optical quality behaviour, showing lower RMS defocus values.

RMS astigmatism (Fig. 3) and coma (Fig. 4) values revealed that lens A and B obtained worse results with decentration, while the aberration-free lens (lens C) performed the best when lenses are placed in their design position inside the numerical eye. When the IOLs are flipped, lens C suffered from increased astigmatism and coma aberrations with decentration. However, in this particular situation, the lens which totally compensates for corneal SA (lens A) obtained the lowest aberration values. In the scenario with properly positioned posterior aspheric

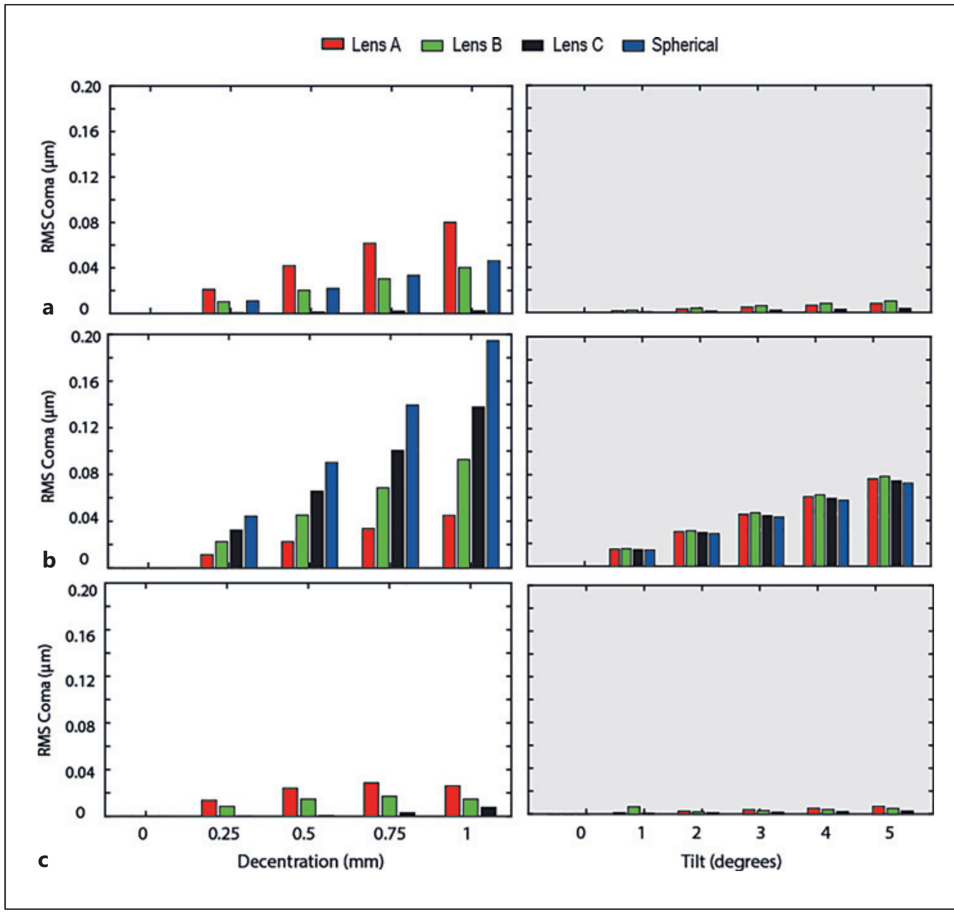

Fig. 4. RMS coma (Z_3^{-1} and Z_3^{1}) values of the designed IOLs for decentration (white background) and tilt (grey background) with each different lens design or condition: aspherical anterior surface IOL on its design position (**a**), aspherical anterior surface IOL placed upside down (**b**), and aspherical posterior surface IOL on its design position (**c**).

IOL designs (Fig. 3, 4c), all lenses improve their optical quality, especially lens C with an aberration-free design.

By correlating the results shown, it can be assumed that the optical quality depends on the amount of SA correction provided by the IOL, especially for decentration. In case of tilt movement, the effect on optical quality is less dependent on IOL design, which is in agreement with previous studies in which lenses were correctly placed in their design position but suffered from decentration and/or tilt [22–25, 34].

Since the absence of IOL decentration and/or tilt after implantation in the capsular bag cannot be guaranteed, the main conclusion that can be drawn from the results is that an IOL with an aberration-free design, which does not add any fourth-order Zernike SA aberration, is the best choice when minimal postoperative errors of decentration or tilt are predicted. If there is a strong risk of IOL flip during surgery, a lens with a design that fully compensates for fourth-order Zernike SA is the best choice regarding the RMS wavefront aberrations. Otherwise, in the IOL flip situation, an aberration-free IOL or a spherical IOL (without aspheric surfaces) are the worst options. However, if only correct IOL placement can be assured during surgery, in terms of no IOL flip, the IOL designed to partially compensate the corneal SA including asphericity on its posterior surface is the better possible option, even in the presence of decentration or tilt. The drawback of the posterior aspheric surface IOL designs is the asphericity value is much higher, compared with the lenses including the asphericity on its anterior surface (see Table 2), which could lead to some complications during the IOL manufacturing.

Furthermore, the study contains some limitations in analysing the variation in optical quality of different IOL designs inside the model eye. The main limitation of this study is probably the use of a single +27.00 D IOL with a shape factor +0.64. However, considering that a large number of implanted IOL have a lower IOL power than our selection, and that the detrimental effects on optical quality are higher for IOL designs other than the equiconvex (shape factor equal to 1), the results found in this study can be considered as an upper limit for the expected effects in an IOL implanted in an upside-down position.

Statement of Ethics

A study approval statement is not required as this research article do not involve any human participant to data acquisition. For that reason, the approval by a human research Ethics Committee is not necessary.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Sources

This research was supported by Ministerio de Ciencia, Innovación y Universidades (Grant No. PID2020-113822RB-C21 and Grant No. PID2020-114311RA-I00), and Gobierno de Aragón (Grant No. E44-20R and Grant No. T24-20R).

Author Contributions

Marta Lacort: investigation, data analysis, and writing – original draft; Jesús Pérez-Gracia: investigation, data analysis, software, and writing – original draft; Jorge Ares: conceptualization, supervision, and writing – reviewing and editing; Laura Remón: methodology, conceptualization, supervision, and writing – reviewing and editing.

Data Availability Statement

All data generated or analysed during this study are included in this article. Further enquiries can be directed to the corresponding author.

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