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Inverted meniscus intraocular lens as a better optical surrogate of the crystalline lens

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Abstract: Current intraocular lenses (IOLs) are designed to substitute the cataractous crystalline lens, optimizing focus at the fovea. However, the common biconvex design overlooks off-axis performance, leading to a reduced optical quality in the periphery of the retina in pseudophakic patients compared to the normal phakic eye. In this work, we designed an IOL to provide better peripheral optical quality, closer in that respect to the natural lens, using ray-tracing simulations in eye models. The resulting design was a concave-convex inverted meniscus IOL with aspheric surfaces. The curvature radius of the posterior surface was smaller than that of the anterior surface by a factor that depended on the IOL power. The lenses were manufactured and evaluated in a custom-built artificial eye. Images of a point source and of extended targets were directly recorded at various field angles with both standard and the new IOLs. This type of IOL produces superior image quality in the whole visual field, being a better surrogate for the crystalline lens than the commonly used thin biconvex intraocular lenses.

1. Introduction

The crystalline lens in the human eye is thick and presents a gradient index distribution [1]. In combination with the cornea, it produces an overall image quality that is reasonably good in a large visual field. The human eye features a somehow wide-angle design with at least 40 degrees of field [1]. At larger eccentricities, peripheral astigmatism increases, becoming the dominant aberration and degrading image quality [2,3]. Peripheral image quality of the eye traditionally received less attention because it was assumed that the resolution of the optics was superior to that of the retinal sampling. The common view was to consider that the limitation of peripheral vision was mainly imposed by retinal and neural factors [4]. However, several experiments have shown that additional defocus in the periphery can affect detection thresholds but not discrimination thresholds [5]. Abnormally degraded peripheral optics also produces lower contrast thresholds [6] and reduces the performance of different functional tests, such as navigating steps [7]. These studies suggest that the quality of the peripheral optics in the eye needs to be above a certain level to assure a good quality peripheral vision.

During the last decades, research on peripheral optics in the eye was mainly motivated by myopia research [8]. There are now significant data in large populations studying peripheral refraction and the aberration properties of natural eyes [9–12]. These properties are related to the central refractive state of the subject, although it is still uncertain if peripheral optics has an effect on myopia development or it is simply a consequence. Another group of eyes whose peripheral optics has also been studied are those of patients after undergoing cataract surgery [13]. In this type of procedure, the natural crystalline lens is replaced by an artificial intraocular lens (IOL). An IOL with the appropriate refractive power is selected to optimize focus at the eye's retina,

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substituting in this way the patient's crystalline lens. IOL's design had been developed around optimal image quality at small angles around the fovea and overlooked optical performance in the peripheral retina. The optical differences between IOLs and the crystalline lens are quite notorious; while the thickness of most IOLs is smaller than 1 mm, the crystalline lens is 4 times larger. The crystalline lens has a structure similar to an onion with layers of different refractive index, while IOLs are made of one single material with uniform refractive index. These differences have an impact in peripheral optics of pseudophakic patients. Smith and Lu [14] first examined this topic theoretically, finding that peripheral power errors and oblique astigmatism of pseudophakic eyes were larger compared to phakic eyes. Millodot [15] measured aphakic eyes with a refractometer and compared them with healthy control eyes of people of similar age. More recently, peripheral refraction and aberrations was measured in patients with implanted IOLs and compared them with normal eyes [13]. They showed a significant deterioration of peripheral image quality after implantation of standard biconvex IOLs. Peripheral defocus and astigmatism increased as well as higher order aberrations. Another common phenomenon occurring at the far periphery of pseudophakic patients is the presence of dark shadows, called negative dysphotopsia [16].

In this context, the aim of this work was to search for optical designs of IOLs that can be a better optical surrogate for the natural crystalline lens for peripheral performance. A required condition was to facilitate the surgical process by maintaining a thin lens design, compatible with a small incision. A systematic search of different lenses was performed and an IOL with an inverted meniscus shape was found to produce an improved image quality in the periphery of the pseudopakic eye. Results on the peripheral optical quality provided by simulations and measurements with actual lenses in a physical model eye are presented.

2. Methods

2.1. Ray-tracing simulations

The optical characterization of the wide-angle pseudophakic eye was initially done using ray-tracing in OpticStudio (Zemax LLC, Redmond, WA, USA). The pseudophakic model was based on a wide-angle model of the human eye [17], where the crystalline lens was replaced with an acrylic thin lens (refractive index: 1.54) of equivalent refractive power.

2.2. Physical model eye

A physical model of a pseudophakic eye was built. The model had realistic dimensions with a cornea made of PMMA (radius of curvature 7.73 mm, conic constant -0.24), an iris at a depth of 3.55 mm (3-mm pupil diameter), and an IOL holder with variable distance (0.5 to 1.5 mm) from the pupil, simulating a postoperative anterior chamber depth ranging from 4.05 to 5.05 mm. The volume of the artificial eye was filled with distilled water. A board level camera (DFM 72BUC02-ML, Imaging Source, Germany) in a water-tight container with a 200µm glass window was introduced to allow direct recording of retinal images. The camera was mounted on a rotating base where the center of rotation was on the optical axis of the system and the radius ranged from 11 to 13 mm to model different retinal radii of curvature. For each field angle (0, 10, 20, 30 and 40 degrees) the retinal image was optimized for sphero-cylindrical error using trial lenses. Figures and additional details on the artificial eye can be found elsewhere [18]. Inverted meniscus lenses were manufactured and evaluated in the above mentioned artificial eye. Images of a point source and extended targets were directly recorded at various field angles with both standard biconvex and the menicus IOLs inserted.

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3. Results

3.1. Optimized IOL for the periphery: inverted meniscus

The optimized shape of the IOLs for the periphery was that of an inverted meniscus with the convex surface facing the retina and both aspheric surfaces. The curvature radius of the posterior surface was smaller than that of the anterior surface by a factor that depends on the IOL power. This type of lenses improves optical quality in the periphery of the visual field while retaining a similar performance to standard IOLs on axis. Figure 1 shows ray-tracing results in three eyes for different angles of incidence of the light, maintaining the eye's geometrical characteristics: (a) wide-angle model of a normal human eye [17], (b) pseudophakic eye model with a standard biconvex IOL, and (c) pseudophakic eye model with an inverted meniscus IOL.

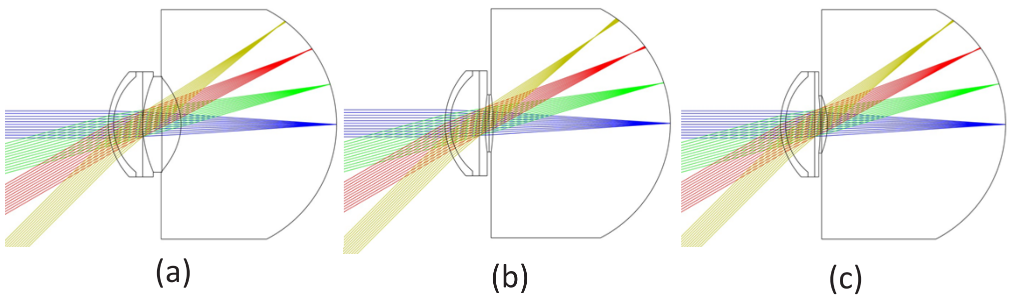

Fig. 1. Ray-tracing in three eye models on axis and for three different retinal eccentricities. (a) Normal phakic eye with natural crystalline lens. (b) Pseudophakic eye model with a standard biconvex IOL. (c) Pseudophakic eye model with an inverted meniscus IOL.

Figure 2 shows the optical performance as a function of retinal eccentricity for the phakic eye with its natural crystalline lens (blue line), the pseudophakic eye with a standard biconvex IOL (yellow line), and the pseudophakic eye with the optimized inverted meniscus IOL (green light), using three different metrics: (a) relative defocus, (b) astigmatism, and (c) RMS of total aberrations in microns (except defocus). Defocus in the natural eye and the inverted meniscus showed similar values, close to 0 D up to 30 degrees, below 0.5 D up to 40 degrees, and below 1 D for 50 degrees, whereas the biconvex IOL showed a relative myopia reaching around -1 D for 40 degrees and -1.25 D at 50 degrees. Astigmatism followed a similar trend in all three cases, increasing continuously with eccentricity, but with values similar to each other in the cases of the natural lens and the inverted meniscus IOL and almost double for the biconvex IOL at all eccentricities. Likewise, RMS showed an increasing trend for all three cases, with the biconvex IOL showing higher values, rising faster with eccentricity.

Figure 3 shows the calculated point-spread functions (PSF) for the three cases at different eccentricities. The PSFs for the standard biconvex IOL subtend larger angles at the periphery as compared to those for the natural eye and the meniscus IOL, which are comparable. Figures 4–6 present two-dimensional maps of PSFs for eccentricities covering 100×50 degrees of retinal field for the phakic normal eye (Fig. 4), the pseudophakic with standard biconvex (Fig. 5), and the inverted meniscus IOLs (Fig. 6).

3.2. Images in an artificial eye with real IOLs

Actual inverted meniscus IOLs were manufactured and tested in the artificial eye previously described. Figure 7 shows the images of a letter chart, recorded on axis for an artificial eye with a biconvex IOL (a) and with a meniscus IOL (b). Figure 8 shows the significant deterioration of the letters with the standard biconvex IOL in comparison with the meniscus IOL at 40 degrees.

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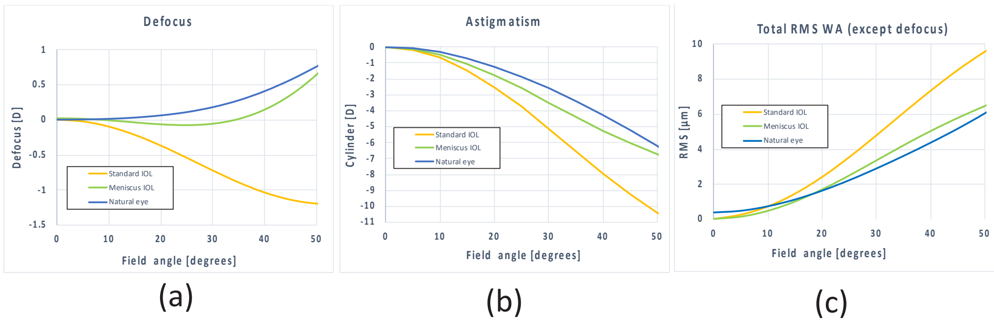

Fig. 2. Optical aberrations as a function of retinal eccentricity for the natural eye (blue) and pseudophakic eyes with a biconvex (yellow) or an inverted meniscus IOL (green). Panels: (a) defocus in D; (b) astigmatism in D; (c) RMS (root mean square) of the aberrations excluding defocus, expressed in microns.

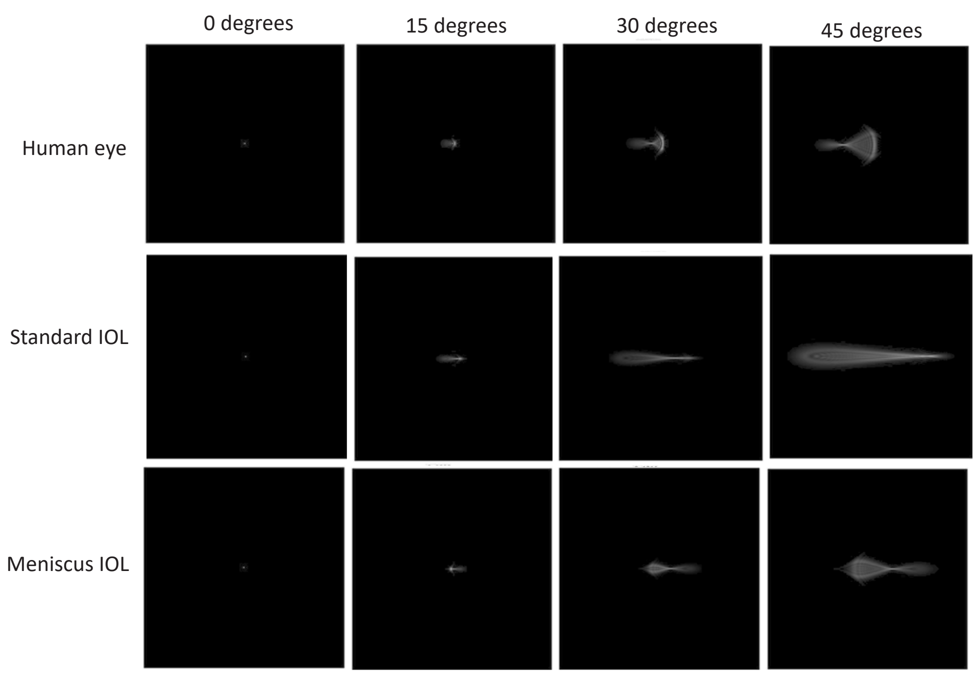

Fig. 3. Point-spread functions (PSFs) calculated from eye models of a phakic human eye, and pseudophakic eyes with a standard biconvex IOL or an inverted meniscus IOL. The extension of the PSFs at the larger eccentricities are significantly increased in the case of the biconvex IOL.

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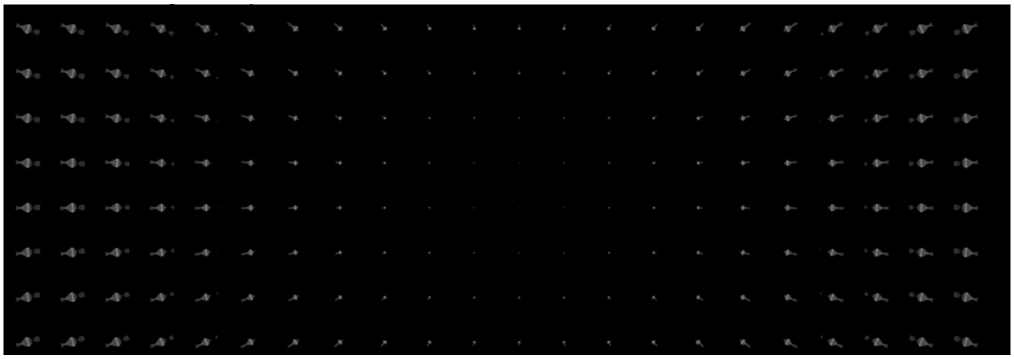

Fig. 4. Two-dimensional set of calculated PSFs for a as a function of retinal location (100 × 50 degrees) in an eye model with its natural lens.

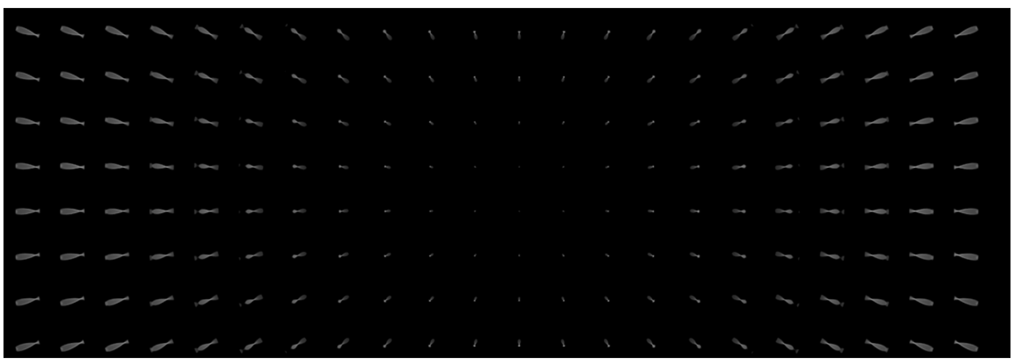

Fig. 5. Two-dimensional set of calculated PSFs for a as a function of retinal location (100 × 50 degrees) in a pseudophakic eye model with a standard biconvex IOL.

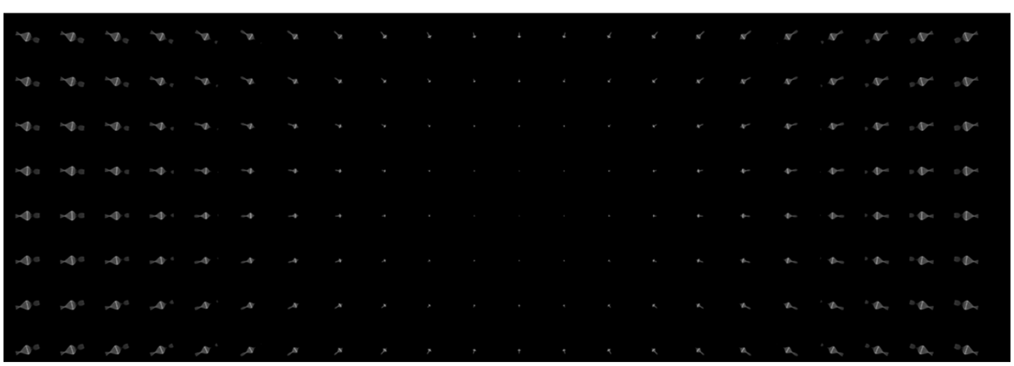

Fig. 6. Two-dimensional set of calculated PSFs for a as a function of retinal location (100 × 50 degrees) in a pseudophakic eye model with an inverted meniscus IOL.

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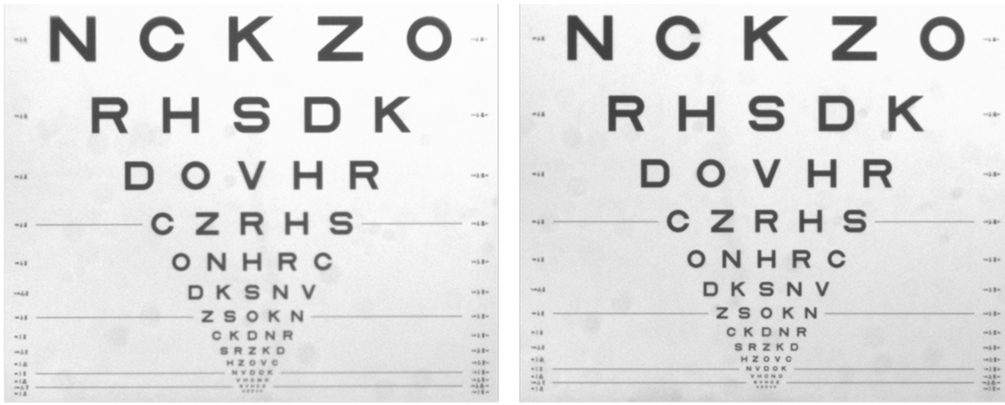
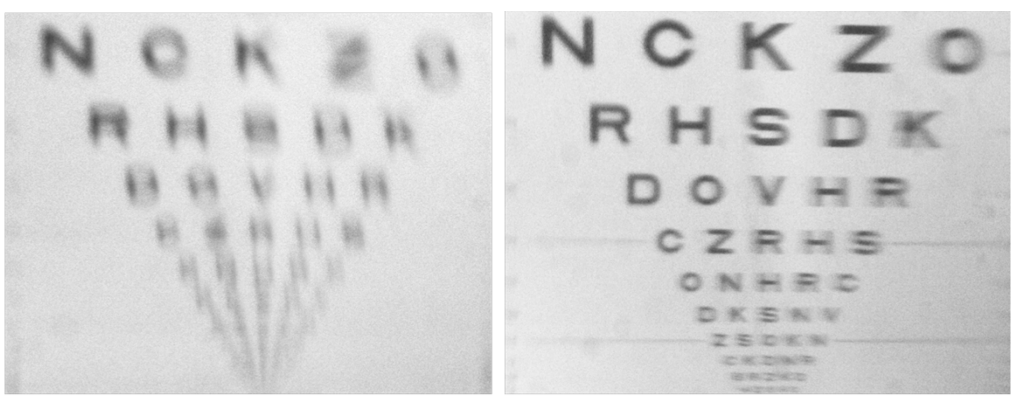


(a) (b)

Fig. 7. On-axis images of a letter chart, experimentally recorded in the artificial eye when furnished with a standard biconvex IOL (a) or an inverted meniscus prototype (b)



(a) (b)

Fig. 8. Images of a letter chart at 40 degrees of eccentricity, experimentally recorded in the artificial eye when furnished with a standard biconvex IOL (a) or an inverted meniscus prototype (b)

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4. Discussion

Although the spatial resolution of the peripheral retina is limited by the photoceptors and neural sampling, this part of the retina has a functional purpose for the development of daily activities. It gives information on patient's spatial orientation and detects rapidly moving objects preventing accidents such as falls, impact of objects and risks in driving [19,20]. The natural optical design of the crystalline lens achieves a moderate optical deterioration as eccentricity increases. This natural protection of our ocular system could be disrupted when a standard biconvex IOL is implanted. It has been reported that a degradation in peripheral optics can affect visual recognition and driving ability [21,22]. This suggest that an IOL providing a better optical quality in the periphery should be beneficial for patient's quality of life.

In a previous work [23], it was suggested an IOL with standard biconvex shape and customized asphericities in each surface to improve peripheral optics. As far as we know, this proposal has not been tested with real lenses.

The inverted meniscus shape that we have proposed as optimal for the periphery here was indeed already used several decades ago [24,25]. A then called "super-reversed intraocular lens" was implanted in nearly 500 patients. The lenses were relatively thick and built in PMMA requiring large incisions. Although it was suggested that this design provided significant advantages, the idea was abandoned. The main reason was probably that at the time, a biconvex lens was perceived as more similar to the crystalline lens. In addition, the image quality on axis in those early inverted meniscus designs was not optimized properly. More recently, in a paper reporting an IOL to correct coma [26], some of the proposed lenses for particular powers (low power lenses) had an inverted meniscus shape. However, the authors did not mention the benefits for peripheral optics.

Peripheral astigmatism could be further reduced by adjusting the shape factor of the inverted meniscus IOL. The design proposed here has posterior radius of 7 mm and an anterior radius of 24.79 mm for a 20-D lens manufactured with high refractive index hydrophobic acrylic ($n = 1.54$). This allows some residual astigmatism and peripheral aberrations comparable to those of the natural human eye instead of attempting a full optimization of peripheral optics. This approach seems reasonable considering also anatomical, functional and manufacturing consideration. A full elimination of peripheral aberrations would require a specific retinal radius of curvature to match the Petzval curvature of the system in order to utilize the improved optical performance. The proposed design maintains peripheral aberrations at a natural magnitude while providing peripheral depth of focus to perform similarly in different retinal shapes. It could be also considered specific IOLs designed to match the shape of the retina that is fundamentally different depending the central refraction [27].

Eliminating additional peripheral aberrations requires designing a lens that has an even steeper posterior surface (and more negative anterior) an approach that poses increasing manufacturing challenges both in the tolerancing associated with the alignment of the anterior and posterior surfaces and the manufacturing tolerances of the surfaces.

The results presented were obtained for a 3-mm pupil diameter because this is a common size in pseudophakic patients. However, we have also simulated for larger pupil sizes obtaining a smilar relative improvement in peripheral optics for the meniscus lens.

In addition to providing better peripheral image quality, the inverted meniscus shape has an additional advantage: its principal plane is located outside of the IOL's optics, posteriorly to the posterior surface. This requires a higher power lens calculation for any given eye in comparison to a calculation based on a biconvex design that has its principal plane in the optic. This displacement of the principal plane is approximately 0.5 mm when comparing a 20D biconvex and a 20 D meniscus manufactured as described above. This direction of shift is associated with a difference about 0.5 D (typical) of dioptric power in the IOL, a condition that has an equal effect in the theoretical A-constant of such a lens. The higher power lens implanted at a greater

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(equivalent) depth is in favor of reducing the shift of the nodal points of the eye that may have unknown impact on peripheral distortion. Also, it brings the overall Petzval curvature of the pseudophakic eye closer to the average anatomical radius and reduces peripheral defocus.

The inverted meniscus IOLs were actually manufactured and recently implanted in a group of patients [28]. The clinical results confirmed the theoretical predictions showing a reduction of peripheral astigmatism and a better contrast detection in the periphery.

5. Conclusions

An IOL designed to control field curvature and to reduce peripheral astigmatism in the pseudophakic eye has been proposed. It has an inverted meniscus shape and showed, in an artificial eye, superior image quality in the whole visual field. A better peripheral optical quality has been also demonstrated in an artificial eye with real IOLs. Further research is required to establish how this improvement in optical image quality translates to a measurable increases in patient`s quality of life, contributing to a reduction in the risks of falls and accidents.

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Disclosures. Some of the authors are co-inventors in patent applications of the described IOL's concept.

Data availability. Data of this paper are not publicly available, but it may be obtained from the corresponding author upon reasonable request.

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