Optical performance of a monofocal intraocular lens designed to extend depth of focus.

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ABSTRACT

Purpose

To test the performance of a new monofocal intraocular lens, intended to extend depth of focus (Tecnis® Eyhance, ICB00) (ICB-IOL), in comparison to a time-tested standard monofocal IOL (Tecnis® 1-piece, ZCB00) (ZCB-IOL) of same platform and material.

Methods

Assessment of the optical performance of the two IOLs was made *in-vitro* using an optical test bench with a model eye. The spherical aberration (SA), modulation transfer function (MTF) and the area under the MTF (MTFa) were obtained for pupil sizes ranging from 2.0mm to 5.0mm. Through-focus MTFa curves between -3.0D to +1.0D were obtained with three pupils (2.0mm, 3.0mm and 4.5 mm). Halo formation was also assessed for both lenses.

Results

The ICB-IOL had slightly worse optical quality at its best focus (i.e., lower MTF scores at distance vision) and more negative SA than the ZCB-IOL for pupils ranging from 2.0mm up to 3.0mm.The maximum of the through-focus MTFa curve of the ICB-IOL with a 2.0mm pupil, shifted to myopic defocus of -0.50 D. For larger pupils (≥3.5 mm), there were no differences of SA, MTF scores and halo energy between the two lenses.

Conclusions

The new ICB-IOL is a modified monofocal lens with 0.50D of additional power in its central 2mm zone and more negative SA values, which induces a myopic shift of the maximum of optical quality and could improve intermediate vision. For pupils larger than 3.5mm, there were no differences between both IOLs.

The new ICB-IOL design would produce photic phenomena comparable to a standard IOL.

INTRODUCTION

Restoring vision by replacing the opacified crystalline lens with an intraocular lens (IOL) remains the main goal of cataract surgery. However, modern-day patients are in general more demanding and have higher expectations regarding visual quality, comfort and spectacle independence after IOL implantation. For that reason, cataract surgery is nowadays performed at increasingly earlier age and has become a consolidated option within the portfolio of refractive procedures.[1] This has prompted the constant evolution of IOLs' designs intending to achieve the best visual function possible, especially at intermediate and near distances, while maintaining perceived good image quality at a far distance. Designs currently available on the market are diffractive, refractive or combined refractive/diffractive ones, with low, intermediate or high addition power each providing distinct vision at different distances. With regard to the IOLs' foci feature, the lenses are commonly categorized as multifocal IOLs (i.e., bifocal and trifocal) and extended range of vision, the latter being commonly referred as extended depth of focus (EDOF) IOLs.[2,3] Effective extension of the depth of focus from distance to intermediate and near distances has been achieved with either, diffractive-based bifocal IOLs which combine low addition and chromatic aberration correction,[4,5,6] or more recently by means of a refractive-based IOL with alternate zones of different focus power and spherical aberration (SA).[7] Examples of these EDOF IOLs are Tecnis® Symfony (Johnson & Johnson Vision, Inc., Ireland) and Mini WELL (SIFI, Catania, Italy) respectively.

The Tecnis® Eyhance IOL, model ICB00 (ICB-IOL) (Johnson & Johnson Surgical Vision, Inc.) is a new monofocal refractive lens aimed at extending depth of focus in comparison to a standard monofocal IOL. The manufacturer's goal with this new design is to offer the patient better visual acuity at intermediate viewing distances -that is required for many important daily tasks- while maintaining the quality and amount of vision the patient gets for far vision. In addition, and according to the manufacturer, the ICB-IOL should not produce more photic nuisance than a conventional monofocal IOL does,[8] although this feature has yet to be confirmed by clinical studies. The ICB-IOL incorporates a modified aspheric anterior surface that differs from that of its predecessor, the Tecnis® 1-piece, model ZCB00 (ZCB-IOL), an IOL that has been widely implanted throughout the world and yields well-known outcomes. [9-12]

The aim of this paper is to evaluate in-vitro the optical performance of the new ICB-IOL by comparison to the standard monofocal ZCB-IOL.

METHODS

Intraocular lenses

Two monofocal IOLs produced by the same manufacturer (Johnson & Johnson Vision, Inc) were included in this study: Tecnis®-1 model ZCB00 (ZCB-IOL) and Tecnis® Eyhance, model ICB00 (ICB-IOL). Both lenses share the same platform, have a biconvex design and are made of the same ultraviolet-light absorbing hydrophobic material with a refractive index of 1.47 (at 35º). In addition, for a 6mm eye entrance pupil (5.3mm at the IOL plane),[13] they both produce negative 4th-order spherical aberration of -0.27μm.[8,14] The studied lenses had the same refractive power (20 D).

The ZCB-IOL is a standard monofocal lens with an anterior aspheric surface and a posterior spherical one. The optical and clinical performance of this lens have been extensively reported in previous works.[9,10,12,14-17].

The new ICB-IOL features a modified higher-order aspheric anterior surface intended to produce a continuous power increase from the periphery to the center of the lens. More concretely and according to a manufacture's specialist, whereas power in the ZCB-IOL increases from the periphery to the center of the lens, the power change in the ICB-IOL is continuous, but faster, with most of the change occurring in the central part of the lens.[8] The posterior surface of the lens is spherical.

Optical quality and halo assessment

The optical performance of the IOLs was evaluated with a test bench that has been described in detail elsewhere,[17,18] and mainly consists of three parts: the illumination system, the model eye and the image acquisition system (Figure A). Since the ICB and ZCB IOLs share the same hydrophobic acrylic material of the Tecnis® 1-piece family of IOLs, their chromatic properties and spectral performances should be very similar, and then, we have considered green illumination (530nm±20nm) exclusively in our experimental tests. The green LED source illuminated either a four-slit test or a pinhole object for MTF measurements [17,19] and halo assessment [20,21,22] respectively. The model eye was formed by an artificial cornea and a wet cell with balanced salt solution where the IOLs were placed. A variable aperture diaphragm, placed in front of the artificial cornea, was used as the entrance pupil (EP) to control the size of the beam on the artificial cornea and hence, the level of corneal SA of the wavefront that impinged upon the tested IOL (Fig. A). Additionally, the EP size also determined the beam size on the IOL plane (referred hereafter to as IOL-pupil).[13] The ratio IOL-pupil to EP was experimentally calibrated to be 0.56. From now on, all the pupil diameters are referred to the IOL plane.[18,23] The cornea was an achromatic doublet (Lambda-X, Belgium) that induced +0.175 µm of 4th-order SA for a 5.0mm IOL-pupil. The model eye with the IOL formed an image of the test object at its best focus that was projected through a 10X infinity corrected microscope onto an 8-bit CCD camera. All the optical elements in the setup were mounted in high-precision mechanical holders with three axis (X, Y and Z) micrometer-precision adjustments.

The modulation transfer function (MTF) of the IOLs placed in the model eye was measured at their best focus plane for distance vision. This focus plane was experimentally determined as the one that maximized the MTF for a 3.0mm IOL-pupil and was set as the origin for defocus (i.e., 0.00D).

The through focus MTF curves were obtained between -3.00D to +1.00D in 0.10D steps with three IOL-pupil sizes: 2.0mm, 3.0mm and 4.5mm, the last two simulating photopic and mesopic illumination conditions in the clinic. Additionally, the optical quality was also evaluated with the area under the MTF metric (MTFa) given its potential significance as preclinical metric.[14,17] The MTFa was obtained by integrating the corresponding MTF values from 0 to 50 cycles/mm as reported elsewhere. [14] The MTF was computed from the images of the four slit object, and more specifically, from the modulus of the Fourier transform of the line spread function of each slit (i.e., four MTF curves).[19] The mean and standard deviation of the MTF and MTFa were derived from this four measurements. The higher the MTFa value, the better the optical quality of the IOL.

For the halo assessment, we determined the halo energy as illustrated in Figure B. The image provided by the CCD camera (linear scale of intensity), consisted of the sharp and intense image of the pinhole (referred from now on as core) surrounded by a faint halo (Figure BA). When the image was displayed in logarithmic scale of intensity (Fig. BB),[16, 21, 22, 24] which is a closer representation of how the human eye would see the image, the halo became quite evident.

In the image in logarithmic scale, we computed the log-transform energy of the region of interest as:[16, 18, 25]

$$\boldsymbol{E_R = \sum_{n\,pixel}^{n \in R} \log\big(e(n)\big)} \qquad \text{Eq. (1)}$$

where *R* stands for either the total image, or the core region - inside the dash black circle in Fig. BB-, or the halo –outside the dash black circle in Fig. BB- (*R*= total, core or halo), *n* is a pixel contained in the *R* region, and *e(n)* is the pixel gray level. For each pupil size, the log-transform energy obtained with Eq. 1 in the core and halo regions (E_{core} and E_{halo} respectively) were compared to E_{total} and expressed as percentages. This normalization is necessary for quantitative comparison of the pinhole images recorded with different pupil sizes and thus with different energy. Moreover, since the human eye responds to differences of energy, we have also computed the non-normalized differences between the core energy and the halo energy, which estimates the weight of the halo in the image: the larger the difference of energy the lower the weight of the halo. The uncertainty in the computed values of the energy was basically due to the precision in the determination of the size of the core. Assuming an uncertainty of ±1 pixel in the diameter of this region of interest, the highest error corresponded to the lower IOL-pupil (2.0mm) and was 5% for both IOLs.

Wavefront aberrations measurement

The high-order wavefront aberrations of the IOLs were measured from IOL-pupils ranging from 2.0mm to 5.0mm as reported in Reference 26, modifying the optical configuration of the test bench. As shown in the layout of Fig. C, the artificial cornea was removed from the setup and the microscope and CCD camera were replaced by an aberration free collimating lens and a Shack-Hartmann wavefront sensor (HASO 76, Imagine Optics, France). This sensor has an array of 76x100 microlenses, thus providing an excellent spatial resolution during wavefront sampling, and a maximum aperture size of 8.7x11.4 mm. Wavefront fitting was made with a linear combination of 32 Zernike polynomials from 3rd to 6th order. Each wavefront was measured three times to obtain the mean value and standard deviation of the Zernike coefficients.

Finally, we also computed the wavefront aberrations of the achromatic lens used as artificial cornea. They were obtained versus IOL-pupil size by ray tracing simulation using a dedicated software (Zemax OpticStudio, Zemax Europe Ltd) and the lens parameters (curvature radius, thickness and refraction index) provided by the manufacturer.

RESULTS

MTF measurements

Figure 1 shows the influence of pupil size on the MTFs of both IOLs. For IOL-pupil sizes of 2.0mm and 3.0mm, the MTF curves of the ZCB-IOL were nearly diffraction limited, while the ones of ICB-IOL were lower, indicating worse optical quality. For larger pupils, the MTF curves of both IOLs tended to decrease and get closer. Overall for both IOLs, it is worth remarking the close coincidence of their curves in the range of spatial frequencies of primary interest (0 to 50 cycles/mm).[14,17]

The MTFa metric versus IOL-pupil size is shown in Figure 2. For pupil sizes lower than 3.5mm, the ICB-IOL had smaller MTFa than ZCB-IOL. For larger pupils, the MTFa values of both IOLs were similar within the experimental uncertainty, and tended to decrease, the later showing the deleterious influence that the increase of the pupil size has on optical quality.

The through focus MTFa curves of the ZCB-IOL and ICB-IOL, obtained with IOL-pupils of 2.0mm, 3.0mm and 4.5mm, are shown in Figure 3. Given the monofocal design of both lenses, the curves showed just one peak of maximum MTFa that corresponds to the best focus of the lenses for distance vision.

For both IOLs, the smaller the pupil, the wider the MTFa peak, proving that regardless of the IOL design, there was an effect of focus extension produced as a consequence of reducing the pupil size. With a 2.0mm IOL-pupil, the maximum MTFa of the ZCB-IOL was higher than the one of the ICB-IOL (45.69±0.23 versus 40.61±0.49) and very interestingly, there was a myopic shift of -0.40D in the position of the MTFa peak of the ICB-IOL (Fig. 3A). Even at this position, however, the MTFa value reached by the ICB-IOL was not higher than that of ZCB-IOL. With a 3.0 mm IOL-pupil (Fig. 3B), the maximum MTFa of the ZCB-IOL was still slightly higher (46.11±0.58 versus 42.79±0.77 in the case of the ICB_IOL) while such differences between both IOLs practically vanished with the 4.5mm IOL-pupil (Fig. 3C). With this pupil, the MTFa peak of both IOLs shifted slightly towards hyperopic defocus (+0.20D).

Wavefront Aberration

The cornea of our model eye induced positive 4th-order spherical aberration (SA) (Figure 4) to mimic the natural aberration of the human cornea. The maximum SA was +0.175 µm for a 5.0mm pupil at the IOL plane. Although this value is somehow lesser than the amount reported on average for the human cornea, +0.27 µm for a 6.0mm entrance pupil (5.3mm at the IOL plane),[27] Wang et al.,[28] found that 15.4% of their patients had corneas with SA values smaller than +0.2 µm.

The most significant high-order aberration found with both IOLs versus pupil size was negative 4th-order SA (Figure 4), logically intended to compensate for the positive corneal SA. With the 3.0mm IOL-pupil, the wavefront aberration of the ICB-IOL also showed small contributions of positive 6th-order (0.028±0.001) and negative 8th-order SA (-0.018±0.001). The rest of high-order aberration terms were negligible small for all pupil sizes.

For IOL-pupil sizes lower than 3.5mm, the ICB-IOL lens had SA values more negatives than ZCB-IOL. For instance, with a 2.0mm IOL-pupil the SA of ICB-IOL is, in absolute value, 3.7 times larger than the SA of ZCB-IOL (-0.056±0.003 µm versus -0.015±0.003 µm respectively). For larger pupils both lenses had very similar SA values.

Halo assessment

The images of the pinhole as a function of the pupil size, obtained with the model eye including either ZCB-IOL or ICB-IOL, are shown in logarithmic scale in Figure 5 since it better approaches human perception. With both lenses, halos around the pinhole image could be hardly observed for IOL-pupil sizes up to 3.0mm, but became apparent for larger IOL-pupil sizes of 4.0mm and 5.0mm.

The relative energy of the core and halo to total energy (all calculated with Eq. 1), are shown versus IOL-pupil size in Figures 6(A) and 6(B) respectively. On the other hand, Figure 6(C) shows the non-normalized energy difference between the core and halo regions.

In the case of the ZCB-IOL and for IOL-pupils ranging from 2.0mm up to 3.5 mm, a constant, high fraction of the energy (≈60%) was correctly focused on the core, while with the ICB-IOL we found less energy correctly focused. Conversely, there was more energy spread to the halo with the ICB-IOL. Not surprisingly, ICB-IOL showed in this pupil range, smaller values of the energy difference than ZCB-IOL (Fig. 6(C)), indicating images with more significant halos with ICB-IOL. This trend could already be acknowledged from Fig. 5 where the halo for the 2.0mm IOL-pupil with the ICB-IOL was clearly more visible and larger than that of ZCB-IOL, but was only slightly more visible and larger for the 3.0 mm IOL-pupil. The differences between the two IOLs tended to reduce for increasing pupils. As such, for mesopic and scotopic pupils (≥4.0mm), both IOLs exhibited very close results. The halo energy for both IOLs increased with pupil size (Fig. 6(B)), reaching similar maximum values for the 5.0mm IOL-pupil: 71.9±1.8 % (ZCB-IOL) and 68.5±1.7 % (ICB-IOL). Closely related, the smaller value of energy difference occurred for this IOL-pupil (Fig. 6(C)), which accounts for the significant halos observed in Fig. 5 with both IOLs.

A summary of the results versus IOL-pupil size is presented in Table 1.

DISCUSSION

To our knowledge, this is the first paper that studied *in-vitro* the optical performance of the new monofocal Tecnis® Eyhance model ICB00 (ICB-IOL) whose optical design aims at extend the DOF in comparison to a standard monofocal lens, to provide better intermediate vision, while keeping similar distance vision and comparable incidence of photic phenomena (glare and halo). A meaningful comparison has been carried out by choosing the Tecnis® 1-piece model ZCB00 (ZCB-IOL) as the standard monofocal lens to compare with, because both IOLs, manufactured by the same company, share basic features such as platform and material. Therefore, the fundamental difference between both designs is the modified aspheric anterior surface of the ICB-IOL that is referred by the manufacturer as a continuous higher-order aspheric surface. We have found that this modification in the optical design of the ICB-IOL has a measurable impact on the optical quality (Figures 1, 2 and 3), the SA (Fig. 4) and halo energy (Fig. 6) for relatively small IOL-pupil sizes (below 3.5mm). In contrast, for larger IOL-pupils (equal and above of 3.5mm) the results of the new ICB-IOL tend to be very similar to the standard monofocal ZCB-IOL.

The negative values of SA versus pupil obtained with the ZCB-IOL (Fig. 4) are in good agreement with previous results reported with multifocal and EDOF Tecnis® IOLs that share the same aspheric design.[26,29,30] The measured experimental values of -0.28±0.01μm (ZCB-IOL) and -0.27±0.01μm (ICB-IOL) for 5.0mm IOL-pupil, would fully compensate for the +0.27μm value of the corneal SA of a representative average human cornea.[27,28] Interestingly, we have found differences between the SA values of both IOLs for IOL-pupils lower than 3.5mm and it is in this range of small pupils where worse MTF curves (Fig. 1) and lower MTFa values (Fig. 2) are obtained for the new ICB-IOL in comparison to ZCB-IOL. Moreover, comparing the through focus MTFa curves of the two IOLs (Fig. 3), the largest differences occurred with the smallest IOL-pupil (2.0mm). For this pupil in particular, the MTFa curves of both IOLs are considerably broader, proving that small pupils are an effective strategy to expand DOF in general,[31] although they require good lighting. More importantly, in comparison to the standard ZCB-IOL, the MTFa curve of the new ICB-IOL showed a myopic shift of -0.40D (Fig.3A). To explain this result, we recall that for small pupils the ICB-IOL induced more negative SA than the standard ZCB-IOL, and they were larger (in absolute value) than the SA of the cornea (Figure 4). Then, the model eye with the ICB-IOL must have a remaining negative SA as a result of the insufficient compensation between the positive and the negative SA values of the cornea and ICB-IOL respectively. In a converging optical system with negative SA, the paraxial rays have more dioptric power than the peripheral rays. Thus, in eyes with relatively large pupil (e.g. mesopic illumination conditions) and negative SA, the emmetropia condition is achieved when the circle of least confusion lies on the retina, with the paraxial and peripheral rays focused in front of and behind the retina respectively. Since the eye focusing with small pupils relays only in the paraxial rays, there would be a myopic shift of the best focus condition, as experimentally observed in the case of the ICB-IOL (Fig. 3A). This result confirms the power increase from the periphery to the center in the design of the new ICB-IOL. More concretely and in comparison to the standard ZCB-IOL, there is an additional power close to +0.50D in the central 2.0mm region of the lens, which is based on the larger negative SA of the ICB-IOL with this IOL-pupil (Figure 4). Since the differences between the SA of the two IOLs decreased from 2.0mm to 3.0mm and were practically equal for IOL-pupils larger than 3.5mm, one can conclude that the aspheric curvature of the ICB-IOL originates the +0.50D additional power in the central 2.0 to 3.0mm region and decreases towards the periphery of the lens. This is the basis for the intermediate performance and extension of the depth of focus with this new design, which could improve intermediate vision, especially in high light conditions and/or small pupils.

Several studies have additionally shown that higher-order aberrations, particularly SA, helps to increase the DOF.[32,33] However, the addition of SA to increase the DOF has the potential drawback of lowering the visual acuity (VA).[34] In the clinic, Rocha et al.,[35] and Marcos et al.,[34] found larger DOF in patients implanted with spherical IOLs (i.e., eyes with higher SA) than in patients with aspheric IOLs that reduced the total SA of the eye. Other studies however, failed to find statistically significant differences in DOF between patients implanted with aspheric IOLs with negative SA, aspheric aberration-free IOLs, and spherical IOLs.[36,37] Neither did XianHui et al. find differences in the DOF of eyes with different amounts of 4th-order corneal SA implanted with the same aberration free IOL model.[38] More recently, Belluci et al.[39] reported, in comparison to an aspheric monofocal IOL, greater depth of focus with the Mini Well® IOL, a lens based on alternating positive and negative SA in the central 3.0mm optical zone. Camps et al.[26] measured large negative 4th-order (-0.13±0.01 μm) and positive 6th-order (0.12±0.01 μm) SA within this 3.0mm zone of the Mini Well IOL. Since the experimental SA values of the ICB-IOL are much smaller (Fig. 4), it can be ruled out that the DOF expansion with this new monofocal lens be based on a SA design.

With regard to the differences on optical quality between the ZCB-IOL and ICB-IOL accounted by the MTFa metric and its implication in the clinic, Alarcon et al.[14] found a high correlation between the MTFa metric and clinical VA of pseudophakic patients. The results led the authors to suggest that the MTFa metric could predict clinical average VA, thus becoming a preclinical metrics. More recently, Vega et al.[17] stated that the estimation of achievable VA, as non-linear function of variable MTFa, showed limiting behavior for IOLs with larger MTFa values, i.e. lenses with higher imaging quality. As a consequence, beyond an MTFa threshold, VA tended asymptotically to the best value clinically achieved in the patients, and any further increase in the imaging quality of an IOL (i.e., MTFa values above the threshold) did not translate into VA improvement. With the 3.0mm IOL-pupil, the best MTFa of both IOLs (ICB-IOL=43.15±0.43, ZCB-IOL=46.10±0.33) were far larger than the reported threshold for the MTFa (≈20),[17] and then, one would not expect that the best VA with the new ICB-IOL model be worse than with the standard ZCB-IOL. Nevertheless, clinical studies are needed to either confirm or refute this prediction.

Concerning the halos, the ICB-IOL lens showed on the optical bench, for mesopic and scotopic pupils (≥4.0mm), similar values of energy correctly focused on the core region (or conversely spoiled in the halo) compared to the standard monofocal (Fig. 6). Thus, the new design of the ICB-IOL is more likely to induce similar level of photic phenomena, if any, as to the ZCB-IOL, although clinical studies, yet to be performed, are mandatory to confirm or refute this prediction.

Regarding the differences found in the spherical aberration (SA) within the small central area between the two IOLs, Taketani and Hara, [40] have shown that SA was negatively correlated with dioptric power in the case of the Tecnis ZA9003 aspheric IOL (a lens made of the same material and with the same optical design as the Tecnis ZCB00 IOL of our study). Then, additional work is still necessary to check if the differences of SA we have found between ICB00 and ZCB00 with lenses of +20.0D, are maintained for other dioptric powers. This would be especially relevant in the case of low and high dioptric values because it could provide very valuable information on the performance of the new ICB00 design in the case of highly myopic and hyperopic eyes respectively.

Finally, our results have shown that the ICB-IOL is a modified monofocal lens with 0.50D of additional power in the central 2 mm zone. With regard to the potential impact that this new design may have on near vision, one could argue that pupil miosis would occur when looking at near, a situation under which the ICB-IOL has shown the capability, in the optical bench, of producing a myopic shift related to the power increase on the central region of the lens. However, near tasks at 30-40 cm that demand good quality of vision require add powers of 3.0-2.5D, which are significantly larger than the maximum additional power (≈0.50D) that the lens is able to provide. ~~Furthermore, despite the potential to extend the range of vision of the ICB-IOL, it is yet a monofocal design~~. Preliminary clinical results (N. Garzón, private communication) evidences that the ICB-IOL defocus curve is slightly broader than the one of standard ZCB-IOL, but still has the typical 'Λ-like monofocal shape' with a single visual acuity

(VA) peak for distance vision (0.0D defocus). Thus, it would not be realistic to expect that the ICB-IOL could compete in near vision with multifocal IOLs that provide the pseudophakic patient with additional VA peak at near

To summarize, according to our findings the design strategy of the new ICB-IOL to extend DOF is based on a continuous power increase towards the center of the lens as a result of the increased amount of negative SA that occurs in the central region of the lens (IOL-pupils lower than 3.5mm). The halos measured on the optical bench are comparable to a standard monofocal IOL.

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Figure Captions

Figure 1. MTF curves for IOL-pupil sizes ranging from 2.0mm to 5.0mm at the best focus of the (—) ZCB-IOL and (—) ICB-IOL. The inserts show the MTF curves in the range of spatial frequencies (0 to 50 cycles/mm) used to compute the MTFa metric.

Figure 2. MTFa values (average± standard deviation) for IOL-pupil sizes ranging from 2.0mm up to 5.0mm of the (●) ZCB-IOL and (●) ICB-IOL. These values were obtained upon integration of the corresponding MTF curves between 0 to 50 cycles/mm.

Figure 3. Through focus MTFa curves of the (—) ZCB-IOL and (—) ICB-IOL obtained with IOL-pupil sizes of (A) 2.0mm, (B) 3.0mm and (C) 4.5mm. The arrows indicate the myopic (A) and hyperopic (B) shifts of the MTFa peaks.

Figure 4. 4th-order SA versus IOL-pupil size obtained separately for the artificial cornea (black bars), and each IOL: ZCB-IOL (red bars) and ICB-IOL (blue bars).

Figure 5. Images of the pinhole object formed by the model eye including either ZCB-IOL or ICB-IOL at their best focus for increasing pupil sizes. The images are displayed in logarithmic scale of intensity.

Figure 6. Relative core (A) and halo energy (B) to total energy (all calculated with Eq. 1) and (C) non-normalized energy difference between core and halo, versus IOL-pupil size, obtained with the ZCB-IOL (red bars) and ICB-IOL (blue bars).