

Binocular Visual Simulation of a Corneal Inlay to Increase Depth of Focus

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PURPOSE. To investigate binocular visual acuity and depth of focus when one eye forms images through a typical pupil diameter aperture (4 mm) and the other eye through a small pupil of 1.5-mm diameter.

METHODS. Using a recently developed adaptive optics binocular visual simulator, through focus monocular and binocular visual acuity were measured in three subjects under specially simulated visual conditions: right eyes had “small aperture” vision through a 1.5-mm pupil diameter and left eyes had normal vision through 4-mm pupil diameter. The measurements were performed in photopic and mesopic conditions.

RESULTS. An increase in binocular and monocular (for the small-aperture eye) depth of focus was measured with respect to the 4-mm pupil diameter eye. It ranged from 1 to 1.5 diopter (D) depending on the threshold requirement and the visibility conditions. For photopic conditions, the J2 visual acuity level was reached at 1 D of defocus for the 4-mm pupil diameter case, while for the 1.5-mm, the J2 level was reached at 2.5 D. Binocular summation occurred only in far vision conditions (no defocus added). For near vision, binocular visual acuity closely followed the values of monocular visual acuity for the eye with the smaller aperture.

CONCLUSIONS. The small-aperture effect to increase depth of focus in the human eye was successfully implemented in a binocular visual simulator. Although certain limitations exist, the small-aperture approach provided a simple but attractive solution to increase depth of focus in the human eye. (*Invest Ophthalmol Vis Sci.* 2011;52:5273–5277) DOI:10.1167/iov.10-6436

Optical solutions to improve near vision in presbyopic subjects can be classified as surgical or nonsurgical methods. The nonsurgical solutions include the use of spectacles (bifocals or progressive power lenses) and multifocal contact lenses with profiles designed to improve depth of focus. Although widely used, progressive power spectacles typically require a custom adaptation period due to the strong distortions and aberrations around the progression zone.¹ Multifocal designs in contact lenses are usually limited by physical constraints that regulate the optical quality of near and intermedi-

ate focus at the expense of less quality in the primary (far) focus.

Among the surgical techniques, there are a variety of intraocular lenses (IOLs) designed to improve near vision for presbyopes such as multifocal IOLs² (diffractive or refractive designs) or the so-called accommodative IOLs. Diffractive designs might suffer from glare and scatter light.³ Also, IOL decentrations and tilts might be limiting factors to their optical performance.⁴ On the other hand, the clinical trials with accommodative IOLs present nonclear results so far.⁵ Surgical interventions reshaping the corneal surface to increase depth of focus are also possible solutions (presbyLASIK,⁶ or intracorneal femtosecond laser⁷), although nonreversible.

Another simple alternative to increase depth of focus in the eye is a corneal small aperture inlay.⁸ Yilmaz et al.⁹ and Seyed-dain et al.¹⁰ provided a description of the surgical implantation technique and visual results in patients with an intracorneal inlay (ACI-7000; Acufocus Inc., Irvine, CA). This inlay is a small ring made of polyvinylidene fluoride (PVDF) and contains particles of carbon to make it opaque. It has a thickness of 0.01 mm, a central aperture of 1.6 mm and an outer diameter of 3.8 mm. The surface of the inlay is perforated with 25- μ m holes arranged in a random pattern to allow nutritional flow through the corneal tissue. The average light transmission was 7.5% with a 1600 random-hole pattern. The operating optical principle of this device is notably simpler than the design of a specific and complex phase profile to increase depth of focus. The small aperture with a diameter of approximately 1.6-mm increases the depth of focus of the eye. Figure 1 illustrates this situation schematically. An emmetropic presbyopic eye model focus collimated light (from a point source at infinite) onto the retina through a 4-mm pupil diameter (dark gray) and through a 1.5-mm pupil diameter (light gray). With the small aperture, the point-spread function (PSF) as a function of defocus remains more compact than in the 4-mm case (see the spot diagram of the retina at the bottom-right of Fig. 1 for a series of defocus values). This simple approach provides no multifocality but a theoretically large tolerance to defocus that might be sufficient for performing typical near visual tasks. A disadvantage of the method comes from the reduction in the amount of light reaching the retina and the potential decrease in mesopic/scotopic contrast sensitivity. To reduce this effect as much as possible, the small aperture inlay is implemented only monocularly, expecting that the binocular summation incorporates also the potential increase in monocular depth of focus.

Our intention in this article is to explore how the mechanism of binocular summation works in a special situation like this, when one eye forms the images through a normal pupil diameter (4 mm) and the other eye through a small pupil (1.5 mm). This would complement the previous clinical studies,^{9,10} helping to set the limitations and potential maximum benefits of the small aperture inlay approach. We have used a unique recently developed instrument,^{11,12} an adaptive optics binocular visual simulator, to implement this situation realistically in a noninvasive manner. In addition, this allowed comparing the

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Supported by the “Ministerio de Ciencia e Innovación”, Spain (Grants FIS2007-64765, FIS2010-14926 and Consolider-Ingenio 2010, CSD2007-00033 SAUUL); Fundación Séneca (Region de Murcia, Spain), Grant 4524/GERM/06.

Submitted for publication August 19, 2010; revised November 11 and December 31, 2010, and February 13 and March 7, 2011; accepted March 10, 2011.

Disclosure: **J. Tabernero**, None; **C. Schwarz**, None; **E.J. Fernández**, None; **P. Artal**, Autofocus (C)

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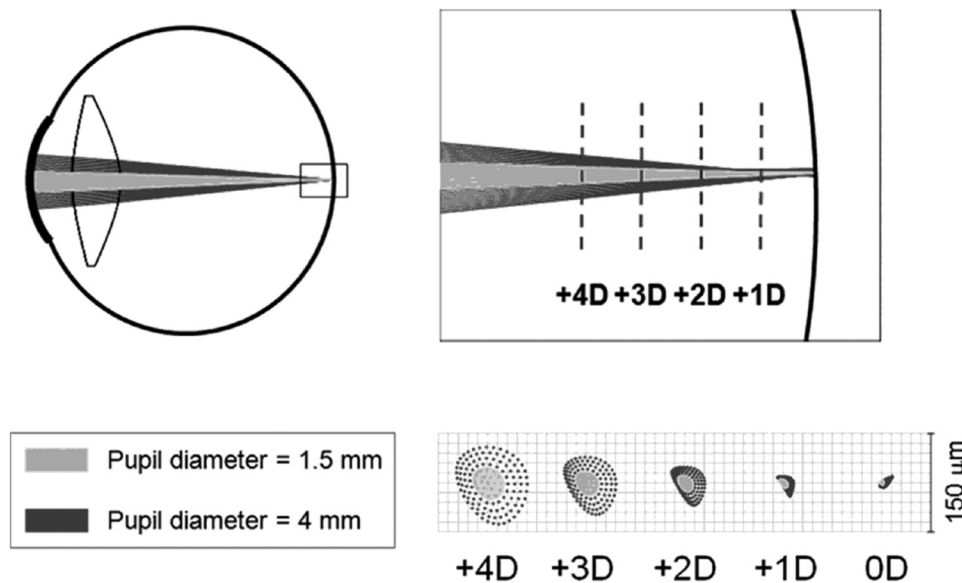


FIGURE 1. Exact ray tracing is performed in an eye model with two different pupil sizes, 4-mm diameter (*dark rays*) and 1.5-mm diameter (*lighter rays*). The area close to the retina is zoomed in for a better observation of the increase in depth of focus. The impact of rays (for both pupil sizes) at different planes separated by a 1 D distance from the retina are shown in the *lower right*.

performance predictions based in optical calculations and the visual results. The optics involved in “small-aperture” vision is analyzed exploring the relationship between visual acuity and the calculated logarithm of the Strehl ratio as a function of defocus. The relationship between both parameters might be useful to infer quality of vision from pure optical measurements. If a clear correlation is established, then objective data might be enough to predict the visual performance of the implants in a variety of situations such as misalignments, ametropias, or particular optical characteristics in the patients’ eye.

METHODS

Binocular Adaptive Optics Visual Simulator

The experimental system was a modified version of the adaptive optics visual simulator reported elsewhere.^{10,11} Figure 2 depicts a schematic diagram of the setup. In the system, the two pupils of the subject’s eyes were projected onto the surface of the phase modulator, and then over the entrance plane of the apparatus. An objective coupled with a microdisplay, of 200 mm focal length, introduced the binocular test at the entrance’s pupils. Those were specifically manufactured for the experiment, being a mask with two apertures of asymmetric diameters and separation between centers of 7.5 mm. The microdisplay was a commercial model (3M Micro Professional Projector MPro120, 3M Projection Systems, St. Paul, MN), with a 9.4 mm diagonal. The programmable phase modulator was based on liquid crystal on silicon (LCOS) technology (X10468-04 model, Hamamatsu Photonics K.K., Hamamatsu, Shizuoka, Japan). The correcting device operated modulating solely phase of linear polarized light of a particular direction (horizontal), which is irrelevant for visual testing. For obtaining the polarized light, the microdisplay was accordingly oriented, because its emission was already polarized. Magnification between entrance and exit pupils of the system was one because twin telescopes, formed by L_1 and L_2 in Figure 2, were used for conjugation of the modulator and those pupil planes. Correct positioning of the pupils was critical in the system. For such a task, a dedicated Charge-Coupled Device (CCD) camera for monitoring the two subject’s pupils simultaneously was used in combination with a flip mirror. Previous calibration allowed for accurately centering of the pupils on the CCD camera. For controlling the location of the pupils, including effective separation of the pupils on the modulator, a periscope was implemented. The periscope was compounded by a pair of plane mirrors and a mirrored prism. Subjects were stabilized to the system using plastic molds with their dental

impressions, preventing changes in position once pupils were aligned. The flip mirror sending light to the pupil camera was also used for alignment of pupils on the liquid crystal on silicon (LCOS) modulator surface. Defocus was generated in the system electro-optically exclusively by the phase modulator. For the current configuration, previous works¹³ have demonstrated that the modulator is capable of inducing ranges of ± 4.8 D of pure defocus with 98% fidelity. Figure 2 shows an example of defocus generation over the two pupils as it was programmed on the modulator, using phase wrapping at 543 nm wavelength.

Subjects and Measurements

Three experienced subjects with normal vision were tested. Ages were 37 (subject 1), 62 (subject 2), and 49 (subject 3) years old. Measurements were performed without paralyzing accommodation in subjects 2 and 3. For subject 1 accommodation was pharmacologically paralyzed with three drops of tropicamide 0.1%, one drop every ten minutes. The study adhered to the tenets of the Declaration of Helsinki and informed consent was obtained from the subjects after they were informed of the nature and all possible consequences.

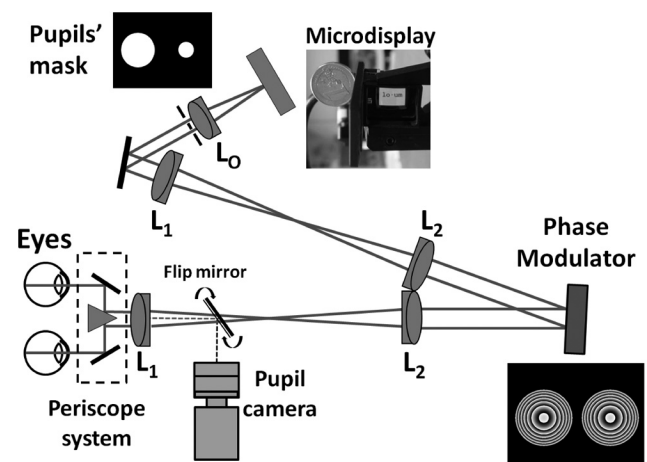


FIGURE 2. Experimental setup for binocular visual simulation. Defocus was generated by the phase modulator. Asymmetric entrance pupils were combined under different luminance conditions in monocular and binocular vision.

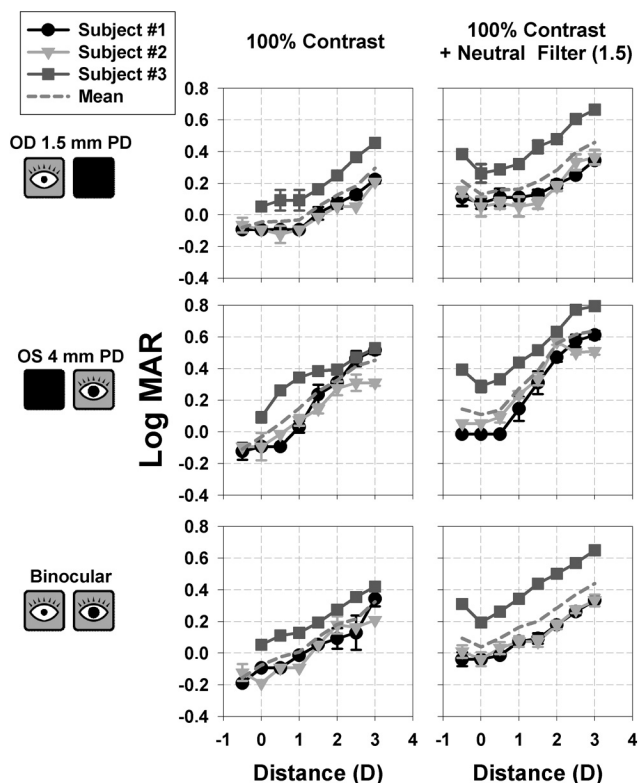


FIGURE 3. Through focus visual acuity (LogMAR) measurements for the three subjects participating in the study. The curves represent monocular measurements for the left and right eyes viewing through two different pupil diameters (1.5 mm, *first row*; 4 mm, *second row*) and binocular measurements (*third row*). *First column* represents the situation when the visual acuity test had 100% contrast letters (photopic condition). In the *second column* the visibility conditions of the test were reduced using a neutral filter of 1.5 optical density. The error bars represent the SD from the mean of three measurements.

Visual acuity as a function of defocus was measured under two luminance conditions: with maximum luminance provided by the microdisplay resembling standard photopic conditions and with a neutral filter with an optical density of 1.5 (transmittance of 3.2%) simulating mesopic conditions. The first set of measurements was taken with a letter (Snellen E) with contrast of 100%. Each set of measurements consisted of three measurements of visual acuity (VA) as a function of defocus, two monocular tests and one binocular test. The monocular tests examined left and right eyes separately. The left eye had an artificial 4-mm diameter pupil conjugated to the pupil plane, while the right eye had a 1.5-mm diameter pupil conjugated with the corresponding plane. The binocular test simultaneously examined these two cases. Measurements were performed in a random order. Subjects were prevented from knowing the artificial pupil size used during the tests. Subjects 1 and 2 had their left eye as dominant, while subject 3 had his right eye as dominant.

A forced-choice procedure with a tumbling E letter was used to estimate VA. First, the letter size was reduced up to the smallest letter that the subject could see. In addition to this reference size, four other sizes (two up and two down) around it were randomly presented to the subject in four different orientations (right, left, up, and down). VA was estimated, expressed by LogMAR units (i.e., decimal logarithm of the minimum angle of resolution) from a psychometric function (four-parameter sigmoidal fit) of correct responses for different letter sizes.

Additionally, optical aberrations were measured for one of the participants in the study (subject 3). A custom-built Hartmann-Shack wavefront sensor was used for this purpose (see details elsewhere^{14,15}). The Zernike terms of the wavefront aberration function

(calculated for a 4-mm pupil diameter) were introduced in optical modeling software (ZEMAX EE; Zemax Development Corp., San Diego, CA) as a phase screen surface and superimposed to a paraxial lens that focuses light at 23.5 mm. The on-axis optical quality for subject 3 was simulated after this procedure as a function of defocus. Then, the distance from the (point) object to the simulated eye model was changed from infinity to 333 mm (from 0 to 3 D) continuously every 0.1 D, reproducing the through focus measurements of the experimental procedure. For each distance, the PSF and the Strehl ratio (peak value of the PSF) were calculated. Similar to the measurements, the procedure was repeated twice, for a 4-mm pupil diameter and for the smaller 1.5-mm pupil diameter.

RESULTS

Through Focus Visual Acuity

Figure 3 summarizes all VA measurements as a function of defocus, for the three viewing conditions (monocular with a 1.5-mm pupil diameter in the first row, monocular with a 4-mm pupil diameter in the second row, and binocular in the third row). The two testing schemes (100% contrast letters and with a neutral filter of 1.5 units of optical density) were plotted on the first and second columns respectively. VA is plotted in the Y-axis of each plot as the logarithm of the minimal angle of resolution (LogMAR). The vergence of the object is given in D, with positive values indicating a nearer object. The different symbols in each plot correspond to the three different subjects tested in this study and the dashed line is the average of the three. A very similar decrease with defocus occurred for the three subjects, although subject 3 showed a lower VA than the other two. This could be perhaps in part explained to the fact that his dominant eye was used for the small aperture. The impact of the neutral filter was to produce a decrease in VA especially significant for the best focus conditions (around 0.2 LogMAR units more with the optical filter).

The effects of the small aperture in depth of focus are better appreciated in Figure 4 showing the average values of VA versus defocus (left plot shows the photopic case with a 100% letter contrast, right plot shows the situation including the neutral density filter). The through focus curve for the monocular case with the 4-mm pupil diameter (triangles) showed a faster increase of LogMAR units than the corresponding monocular case with the smaller pupil (circles). This is exemplified by the fact that there was approximately an increase of 1.5 D of depth of focus if a visual acuity threshold of 0.1 LogMAR (equivalent to J2 in Jaeger notation) is set for the 100% contrast letter case. The J2 level was reached at 1 D of defocus for the 4-mm pupil diameter case, while for the 1.5 mm, the J2 level was reached at 2.5 D. A similar effect was observed with the neutral filter (low visibility conditions), but with a reduction of

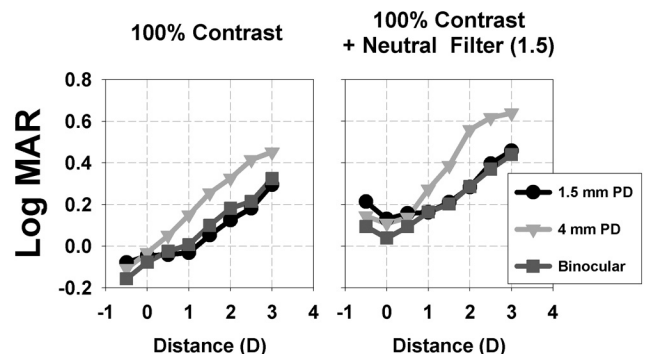


FIGURE 4. Average through focus visual acuity measurements for the three subjects participating in the study.

the depth of focus threshold to J3 (0.3 LogMAR). For this situation, the J3 level was reached at 1 D of defocus with the larger pupil and at around 2 D when the test was performed on the right eye with a 1.5-mm aperture diameter.

Binocular Summation

Figure 4 also describes the mechanism of binocular summation for this particular situation (squared symbols). In general, for the best focus position (0 D), VA was slightly better for the monocular large pupil (4 mm) case than for the small 1.5-mm aperture. Binocular VA (for best focus conditions) improved over the best monocular case (i.e., squares are below the other two data sets in Fig. 4 for zero defocus) showing a classical example of binocular visual summation. The VA improvement for the best focus position was around 0.1 LogMAR units with respect to the monocular pinhole vision in both luminance conditions. For larger defocus values (corresponding to near objects), the small pupil eye clearly dominated over the large pupil eye. In that case, binocular vision closely followed the eye providing the best optical condition. However, binocular vision did not clearly improve over the monocular cases. Additional measurements were performed in subject 3 to test the effects of ocular dominance in binocular summation. However, when the configuration of the pupils was changed (right eye with large pupil and left eye with the smallest pupil) the differences with the previous configuration were nearly negligible (≤ 0.04 LogMAR), even smaller than the SD of the measurements.

Visual Acuity Versus Optical Predictions

Figure 5A shows the calculation of the Strehl ratio (Y-axis, logarithmic scale) versus distance (D). The best focus Strehl ratio corresponds to the measurements from subject 3. The calculations were performed for two different pupil diameters similar to the experimental situation. The dark and light gray solid lines show calculations for a 1.5-mm and a 4-mm pupil diameter, respectively. These plots represent the optical analogues to Figure 4 (VA decay as a function of near distance). Here, the corresponding decrease of optical quality versus near distance is manifested. Figure 5B shows the correlation of these two variables, Strehl ratio (X-axis, plotted in a logarithmic scale) and visual acuity (LogMAR units, Y-axis). The two different plots in Figure 5B represent the two different visibility situations when measuring VA, 100% contrast test letters (Fig.

5B, left plot) and with a neutral filter added (Fig. 5B, right plot). The correlation showed a clear logarithmic profile (converted to linear due to the logarithmic horizontal scale). Therefore, for each plot (Figs. 5A and 5B) a logarithmic function ($VA = VA_0 + a \text{Log}[Strehl]$; solid line) was fitted to the experimental data (empty circles). Both functions in Figure 5B had almost the same slope a , but a different independent term (VA_0) that reflects the luminosity factor. It might be also important to give some indicative numbers of this correlation. In the case of high visibility tests (100% contrast letter), a Strehl value of 0.05 would correspond to a visual acuity of J1 (0.1 LogMAR units). Interestingly, in the case of a lower luminance test (in our case, generated with a neutral filter of 1.5 optical density), the 0.05 Strehl value would correspond to a visual acuity level of J3 (0.3 LogMAR units).

DISCUSSION

The binocular visual simulator presented here provided results that may have an impact on clinical research, particularly in the search of practical solutions to correct presbyopia. Without the need to perform a real implantation, the instrument realistically recreated different aspects of the small-aperture visual conditions, monocular and binocular under different luminances. Although the instrument operated here used physical apertures, the potential of the binocular simulator^{11,12} goes far beyond this. In particular, the use of liquid crystal phase modulators^{13,16} will allow in future studies to explore different aspects that were not yet investigated, like the impact of pinhole decentrations, the effects of different ametropias, or the role of the peripheral corneal zones¹⁷ on the image formation and the achieved quality of vision.

The results of this study accurately set the limits of the small aperture technology to increase the depth of focus and can be used to optimize and customize the visual outcomes. It should be understood as complementary to the clinical works where patients are evaluated after implantation of the inlay. A system such as the one reported here could be used in prescreening potential patients to be treated, to determine the most appropriate eye and other personalized conditions.

The data presented here indicate that a conceptually simple solution such as a small aperture, has the real capability to increase depth of focus with good VA even under mesopic luminance conditions. As it is exemplified in Figure 4, there is

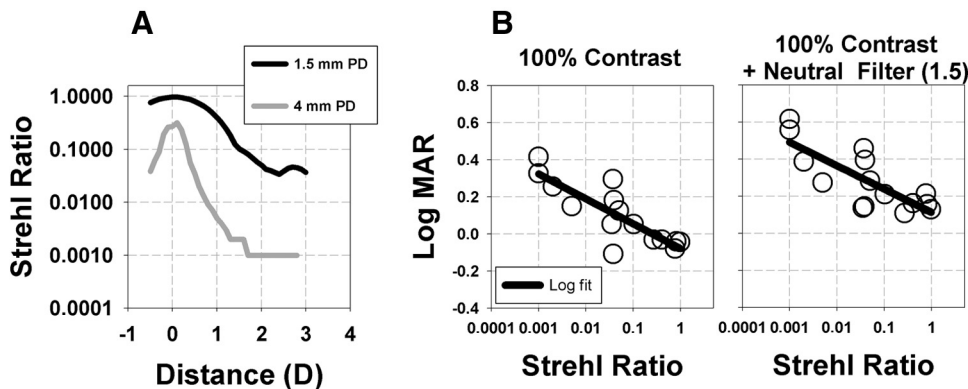


FIGURE 5. (A) The simulated through focus Strehl ratio for subject 3 for the two different pupil diameters studied in the experiments (1.5 and 4 mm). (B) The correlation of the simulations from (A) and the average through focus (monocular) visual acuities shown in Figure 4. This is performed twice corresponding each to the two test-visibility conditions (100% contrast letters and reduced visibility with a neutral filter of 1.5 optical density). The data were fitted to a logarithmic function [$y = y_0 + a \text{Ln}(x)$] shown by a solid line. For the 100% contrast test, the fitted parameters were $y_0 = -0.079$; $a = -0.058$; $R^2 = 0.69$; and for the lowest visibility test $y_0 = 0.113$; $a = -0.055$; $R^2 = 0.59$; both fits were significant $P < 0.001$.

a real measurable effect of extending the range of J2 near vision in more than one diopter. Figure 4 (left panel) also showed that the average binocular acuity of the three subjects was over the J3 level (0.3 LogMAR units) for the 0 to 3 D range of near objects. Clinical studies in patients implanted with the Acufocus ACI-7000 intracorneal inlay showed similar acuity ranges. Seyeddain et al.¹⁰ reported that 95% of 32 patients had J3 or better uncorrected near visual acuity after two years of the intracorneal pinhole implantation. Similar results were reported by Yilmaz et al.,⁹ in a group of 36 eyes implanted with the pinhole. In this case, all eyes with the inlay had an uncorrected near acuity of J3 or better. These results stimulate the research on the topic and enhance the potential possibilities of the small aperture inlay as an effective solution for the increase in depth of focus.

The actual intracorneal inlay (Acufocus ACI-7000) has an annular shape with an inner diameter of 1.6 mm and an outer diameter of 3.2 mm. In future studies, this annular shape could be reproduced in our instrument if the effect of larger natural pupils is to be explored.

The binocular summation with the small aperture in one eye and the 4-mm pupil on the other, presented some a priori surprising results. A binocular improvement in VA with respect to the best monocular conditions for all ranges of defocus might have been expected. This was actually observed for the best focus conditions, but it was not the case for the rest of the defocus range, where the binocular vision closely reassembles the pinhole monocular visual acuity. Perhaps, the visual system was (artificially) forced too much,¹⁸ generating a large retinal disparity between the eye with the pinhole aperture and the companion eye, promoting the suppression of the worst information channel. A clearer explanation for this mechanism needs further research. The possible role of ocular dominance also should be studied. In future studies it will be possible to easily test whether a different combination of pupil sizes would or would not generate binocular summation.

There are certain limitations to the small aperture approach to increase depth of focus. Some of them are intrinsic to the technique, like possible diffraction effects due to the pinhole size or the decrease in the light intensity reaching the retina. However, the results of VA at best focus conditions did not seem to support a significant negative visual effect due to diffraction for that aperture. The effect of the reduction of light intensity in the retina is attenuated with the monovision-type implantation, but this will have to be checked in future studies measuring the binocular contrast sensitivity function. A non-intrinsic problem might be related to the aperture decentration. Typically, the inlay is placed as close as possible to the visual axis, using the corneal reflex as a reference.⁹ If the aperture is not properly centered, a more peripheral part of the cornea would be used to form the retinal image. The optical effect of this situation is difficult to estimate "a priori," although it can be predicted optically if some information on the eye's patient is available. Future studies might use accurate and realistic optical models⁴ to study this effect. In this respect, it is highly relevant to know the correlations between visual acuity and an optical parameter as the Strehl ratio. Obviously, this correlation depends on the conditions of the VA measurements. However, the 0.05 level of Strehl ratio seems to be visually significant. According to our measurements, this quantity can be interpreted in very simple clinical terms as the value that generates J1 vision (0.1 LogMAR) if the visual test is performed in high contrast. If the luminance during the visual test was low, then the 0.05 Strehl value would correspond to J3 vision. This simple association may provide clinicians with an understand-

able average idea of the visual meaning of the Strehl ratio optical quality parameter.

CONCLUSIONS

To summarize, the experimental results presented here will help to better understand the actual visual performance of a method based on the small aperture effect to increase depth of focus in the eye. The binocular summation mechanisms with small-aperture vision in one eye and a normal pupil in the other has been described for the first time and the relationship between objective optical parameters (Strehl ratio) and visual acuity has been given. These results establish a landmark for future studies that will analyze more particular situations of this simple and attractive solution to increase depth of focus.

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