Extended Depth of Focus With Induced Spherical Aberration in Light-Adjustable Intraocular Lenses

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• PURPOSE: To evaluate the quality of vision and depth of focus induced by controlled amounts of negative spherical aberration in patients implanted bilaterally with light-adjustable intraocular lenses.

• DESIGN: Prospective, nonrandomized clinical trial.

• METHODS: Seventeen patients were implanted and treated with appropriate spatial irradiance light profiles. One eye was set for emmetropia, and the fellow eye received an additional aspheric light treatment to induce controlled amounts of negative spherical aberration. We used a Hartmann-Shack sensor to measure the eye's refraction and aberrations for a 4-mm pupil diameter. Decimal visual acuity (VA) was measured using a micro-display placed at 10 m, 60 cm, 40 cm, and 30 cm.

• RESULTS: Eyes treated with aspheric profiles were divided into 2 groups depending on the final amount of induced negative spherical aberration: low [−0.05, −0.10 μm] and high [−0.13, −0.23 μm]. In both groups, the mean uncorrected decimal VA at 60 cm was over 0.90. In the first group, distance VA was 0.97 ± 0.16, but in the second group it was lower (0.76 ± 0.16). As expected, the VA for nearer distances is higher in the eyes with a larger magnitude of spherical aberration (P value < .01): 0.94 ± 0.10 and 0.73 ± 0.16 at 40 and 30 cm, respectively, in comparison with 0.71 ± 0.15 and 0.50 ± 0.14. Binocular summation with the fellow eye, adjusted for emmetropia, produces an excellent binocular distance VA (> 1.10) in both groups.

• CONCLUSIONS: Controlled amounts of negative spherical aberration and defocus can be induced in eyes implanted with adjustable intraocular lenses to enhance near vision. (Am J Ophthalmol 2014;157:142–149. © 2014 by Elsevier Inc. All rights reserved.)

IN THE LAST DECADES, CATARACT SURGERY HAS become a successful procedure to restore vision in many patients. Phacoemulsification, foldable intraocular lenses (IOL), and advances in the calculation of the IOL power have improved the visual outcomes. However, and despite the most recent approaches,[1] refractive surprises[2] (refractive errors higher than 0.5 diopters [D]) after cataract surgery are still frequent, in particular in eyes with a longer-than-normal axial length[3] and in eyes with previous corneal refractive surgery.[4] In addition, values of postoperative astigmatism between 0.5 and 2.0 D, mainly attributable to preoperative corneal astigmatism in combination with what is induced by corneal incisions, are also common.[5,6]

The light-adjustable lens should allow the physician to obtain optimum refractions after cataract surgery.[7,8] These intraocular lenses were successfully irradiated with the appropriate spatial irradiance patterns for in vitro correction of spherical and astigmatic refractive errors.[9] In the last years, several clinical studies have reported good results in the correction of spherical refractive errors (myopia and hyperopia) and also astigmatism with light-adjustable lenses.[10–12] In addition to the correction of refractive errors, light-adjustable lenses can also create higher-order patterns.[13] This offers the possibility to induce controlled amounts of spherical aberration (SA) to increase the depth of focus in patients, allowing for near vision. This approach is implemented and demonstrated in the current study.

METHODS

THE STUDY WAS A PROSPECTIVE, NONRANDOMIZED CLINical trial approved by the ethics committee of the University Hospital "Virgen de la Arrixaca" in Murcia, Spain. All clinical examinations and surgeries were conducted in the Department of Ophthalmology at the Hospital "Virgen de la Arrixaca," Murcia, Spain. Surgeries were completed during 2010 and 2011 in all patients and performed by the same surgeon (one of the authors, J.M.M.). The complete study followed the tenets of the Declaration of Helsinki. Informed consent was obtained by all patients after they were fully informed about the nature and the possible consequences of the procedures.

Seventeen patients were implanted bilaterally with light-adjustable lenses. In 1 of the eyes, postoperative refractive error was corrected with a first light adjustment, and subsequently a second aspheric treatment induced negative spherical aberration to increase depth of focus. Light profiles weighted with varying amounts of asphericity

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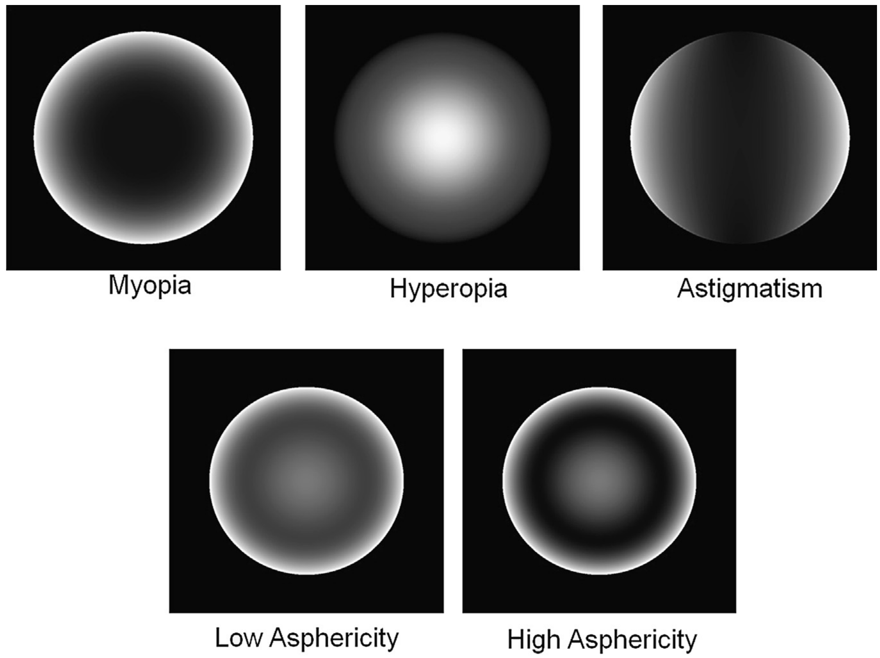

FIGURE 1. Examples of spatial light intensity profiles used to change refraction (Top) and to induce different levels of spherical aberration (Bottom) in eyes implanted with light-adjustable intraocular lenses.

were customized to produce the desired amounts of induced spherical aberration. The fellow dominant eye was treated to achieve emmetropia. The effects of the binocular summation were also evaluated.

• **LIGHT-ADJUSTABLE LENSES AND SPATIAL LIGHT INTENSITY PATTERNS:** Light-adjustable lenses (Calhoun Vision Inc, Pasadena, California, USA) contain photosensitive silicone molecules that enable noninvasive postoperative change of their shape by irradiation with ultraviolet light. The posterior surface of each lens is molded with a UV-absorbing layer to impart the pseudophakic patient with additional UV protection for the retina during the irradiation treatment procedure.[8]

Defocus and astigmatism of an implanted light-adjustable lens can be changed by the application of the appropriate spatially resolved irradiance profile and energy dose. Once the final desired refractive state in the patient's eye is achieved, it is necessary to consume the remaining, unreacted material in the lens by a photo lock-in process. The light-adjustable lens is irradiated using a digital light delivery system (Carl Zeiss-Meditec, Jena, Germany) described elsewhere.[8] It consists of a UV light source, projection optics, and control interface built around a standard slit lamp. A pixelated digital mirror device is used to define a specific high-resolution spatial intensity profile to irradiate the light-adjustable lenses. To adjust the eye's refraction, custom intensity profiles to correct myopia, hyperopia, and astigmatism were used. Secondary treatments used aspheric profiles with different weighted amounts of asphericity to extend depth of focus. Figure 1 shows examples of different spatial irradiance profiles used to adjust refraction (myopia, hyperopia, and astigmatism) and aspheric patterns to change spherical aberration.

• **PATIENTS AND SURGICAL PROCEDURE:** Light-adjustable lenses were implanted binocularly in 17 subjects. The age of patients ranged between 52 and 79 years old (mean 65 ± 9 years). Initial refractions (mean, SD, and range) before treatments are displayed in Table 1. At every visit, the clinical examination included slit-lamp biomicroscopy, intraocular pressure, corneal topography (Atlas; Carl Zeiss-Meditec, Dublin, California, USA), biometry, ocular aberrometry, wavefront-guided refraction, and best-corrected and uncorrected visual acuity. At the preoperative, primary adjustment, and 7-month-postimplantation clinical examinations (see below), ophthalmoscopy and retinal optical coherence tomography were also performed. Owing to the limit in astigmatism correction of light-adjustable lenses in vitro, patients with preoperative corneal astigmatism higher than 2.00 D were not included in the study. The IOL powers were selected based on an internally optimized regression analysis program to obtain a spherical equivalent after surgery near to zero or slightly hyperopic. The IOL powers implanted ranged from 17-25 D.

The light-adjustable lenses were implanted using standard microsurgical techniques for phacoemulsification extracapsular-type cataract extraction. A temporal corneal incision of 2.85 mm was employed. A dispersive

TABLE 1. Manifest Refraction, in Diopters, of Eyes Implanted With Light-Adjustable Intraocular Lenses Before Light Treatments, After All Light Treatments in Eyes Set for Distance Vision (Distance Eyes), and After First Adjustment in Fellow Eyes Treated With Aspheric Profiles in Second Adjustment (Near Eyes); 17 Patients

	Means ± SD (Min; Max)	
	Initial Refraction	Refraction After All Treatments
Distance eyes		
Sphere	+0.85 ± 1.05 (−1.50; +2.25)	−0.05 ± 0.33 (−0.50; +0.50)
Cylinder	−0.98 ± 0.57 (−2.25; 0)	−0.33 ± 0.26 (−0.75; 0)
Equivalent sphere	+0.36 ± 0.97 (−2.00; +1.38)	−0.22 ± 0.38 (−0.75; +0.25)
	Initial Refraction	Refraction After First Adjustment
Near eyes		
Sphere	+0.68 ± 0.83 (−0.50; +2.50)	+0.70 ± 0.42 (0; +1.25)
Cylinder	−0.92 ± 0.59 (−2.00; 0)	−0.55 ± 0.27 (−0.75; 0)
Equivalent sphere	+0.23 ± 0.73 (−0.88; +1.88)	+0.43 ± 0.43 (−0.38; +1.00)

viscoelastic material (Visthesia, Zeiss, Germany, Viscoat 0.5 mL, Alcon Laboratories, Fort Worth, Texas, USA) was introduced into the anterior chamber, and a capsulorrhexis equal to or higher than 5.5 mm was made. Cataract was extracted by stop-and-chop phacoemulsification technique and then cohesive viscoelastic (Healon 10 mg/mL, Abott Laboratories, Abbott Park, Illinois, USA) was also introduced in the anterior chamber. The IOL was introduced in the capsular bag using a lens injector. Residual viscoelastic was aspirated using bimanual technique. The incision was not sutured. A steroidal anti-inflammatory and antibiotic were applied to the eye. The patient was instructed to use UV protective glasses until the second lock-in treatment was completed and the whole process finalized.

• **TREATMENT SCHEDULE AND FOLLOW-UP VISITS:** Preoperative tests were performed within 15 days prior to surgery. The visit schedule was as follows: first light adjustment: 2 weeks after surgery; second light adjustment, or first lock-in (depends on refraction evaluation): 2-3 days after first adjustment; first or second lock-in: 2-3 days after second adjustment or first lock-in; second lock-in: 2-3 days after first lock-in; post second lock-in: 7-30 days after second lock-in; 3-month visit: 10-14 weeks after second lock-in; 6-month visit: 22-26 weeks after second lock-in; 1-year visit: 50-54 weeks after second lock-in.

• **MEASUREMENTS OF REFRACTION AND SPHERICAL ABERRATION:** Wavefront aberrations of the eye were measured using a research prototype near-infrared Hartmann-Shack sensor built in our laboratory[14] and adapted to the clinical environment. This system has more than 220 microlenses for a 5-mm-diameter pupil (the size of each microlens on the eye's pupil is 0.3 mm). The images were recorded in a dark room, allowing a natural pupil diameter larger than 4 mm. To estimate objective refraction, we computed the wave aberration expressed by Zernike coefficients for 3-mm pupil diameter. Spherical aberration was estimated for a 4-mm pupil diameter. The aberrations for the cornea (from corneal topography data using a ray-tracing approach[15]) were also determined. By direct subtraction, the wavefront aberration of the implanted light-adjustable lenses was then determined. This is a similar procedure to that previously used to determine the aberrations of the natural crystalline lens.[16,17]

Objective refractions of whole eye and cornea are calculated from the second-order Zernike coefficients:

$$S = \frac{-4\sqrt{3}Z4}{r^2} - \frac{C}{2}$$

$$C = \frac{-4\sqrt{6}\sqrt{Z3^2 + Z5^2}}{r^2}$$

$$\text{Axis} = \frac{1}{2}\tan^{-1}\left(\frac{Z3}{Z5}\right)$$

where C, S, and Axis are the cylinder, the sphere, and the cylinder orientation, respectively, of the refraction expressed in sphero-cylindrical form with negative cylinder. Z3, Z4, and Z5 are the standard Zernike coefficient indexes.[18] From 5 wavefront aberration measurements, the mean values of refractions were calculated with their experimental errors expressed as standard deviations. Average values of objective refraction were obtained with errors below 0.12 D and 10 degrees (for astigmatic axis). From 5 wavefront measurements, the fourth-order spherical aberration (Zernike coefficient Z12) was determined for a pupil diameter of 4 mm before and after every light treatment.

• **SUBJECTIVE REFRACTION AND VISUAL ACUITY:** Wavefront-guided subjective refraction was also obtained along with each patient's visual acuity. The procedure was as

TABLE 2. Manifest Refractions, in Diopters, of Eyes for Near Vision After Second Aspheric Adjustment to Induce Negative SA in Light-Adjustable Intraocular Lenses, and SA, in Microns, Before and After Second Aspheric Adjustment for 4-mm Pupil Diameter

	Means ± SD (Min; Max)		
	Group 1 (N = 12)	Group 2 (N = 5)	Intergroup Comparison (*P* Value[a])
Refraction post–second adjustment			
Sphere	−0.77 ± 0.41 (−1.50; 0)	−1.35 ± 0.68 (−2.25; −0.50)	**.04**
Cylinder	−0.63 ± 0.38 (−1.00; 0)	−0.35 ± 0.22 (−0.50; 0)	.15
Equivalent sphere	−1.08 ± 0.37 (−1.75; −0.38)	−1.55 ± 0.60 (−2.25; −0.75)	.07
SA[b] pre–second adjustment	+0.058 ± 0.037 (+0.02; +0.15)	+0.085 ± 0.027 (+0.06; +0.12)	.20
SA[b] post–second adjustment	−0.083 ± 0.020 (−0.10; −0.05)	−0.192 ± 0.052 (−0.23; −0.13)	**<.001**

Patients are separated into 2 groups depending on the final value of negative spherical aberration present in the eye for near vision. Group 1: final spherical aberration between −0.05 and −0.10 μm. Group 2: final spherical aberration between −0.13 and −0.23 μm.

[a]Bold = statistically significant.

[b]SA = spherical aberration (Zernike coefficient Z12), in μm.

TABLE 3. Monocular and Binocular Uncorrected Visual Acuity at All Tested Distances After All Treatments in Patients Implanted With Light-Adjustable Intraocular Lenses

	Mean ± SD								
	Group 1 (N = 12)			Group 2 (N = 5)			Intergroup Comparison (*P* Value[a])		
Distances	DE	NE	Binocular	DE	NE	Binocular	DE	NE	Binocular
30 cm	0.35 ± 0.10	0.50 ± 0.14	0.57 ± 0.10	0.35 ± 0.12	0.73 ± 0.16	0.75 ± 0.08	.960	**.009**	**.002**
40 cm	0.50 ± 0.10	0.71 ± 0.15	0.80 ± 0.11	0.50 ± 0.24	0.94 ± 0.10	1.00 ± 0.09	.990	**.007**	**.002**
60 cm	0.74 ± 0.14	0.98 ± 0.19	1.05 ± 0.17	0.79 ± 0.26	0.95 ± 0.16	1.07 ± 0.13	.620	.810	.850
Far (10 m)	1.11 ± 0.21	0.97 ± 0.16	1.14 ± 0.23	1.13 ± 0.14	0.76 ± 0.16	1.19 ± 0.08	.840	**.030**	.640

In all patients, 1 eye is set for distance vision and the fellow eye for near vision depending on final negative spherical aberration induced by an aspheric light treatment. Patients are separated into 2 groups depending on the final value of negative spherical aberration present in the eye for near vision. Group 1: final spherical aberration between −0.05 and −0.10 μm. Group 2: final spherical aberration between −0.13 and −0.23 μm.

DE = eye for distance vision, NE = eye for near vision with negative spherical aberration.

[a]Bold = statistically significant.

follows: objective refraction measured with the wavefront sensor was entered into a standard phoropter rounded to the nearer value in steps of 0.25 D. A computer monitor with an average luminance of 100 cd/m^2 was placed at a distance of 10 m from the subject. The tumbling E letter size was reduced (in steps of 0.09 arc-min) up to the smallest letter that the subject could see. Defocus values of each subject's refraction were optimized in steps of 0.25 D to obtain the highest visual acuity (VA). The optimum subjective focus is usually around 0.50-0.75 D lower than the objective one because of the chromatic shift from the infrared wavefront sensor to the visible spectrum of the monitor. Corrected and uncorrected VA was measured and expressed in decimal units (ie, inverse of the minimum angle of resolution, 1/MAR) for distance vision. Uncorrected VA was also measured for intermediate distance of 60 cm and for near distances of 40 and 30 cm, using a micro-display placed at the appropriate distances. VA measurements were taken both monocularly and binocularly. Although in many clinical studies VA is expressed in logarithm of the minimal angle of resolution (logMAR), we used here decimal units (1/MAR) because it is more intuitive to relate the enhancement in VA with lower values of refractive errors, and in addition the relationship with logMAR is nearly linear in the interval of our VA results, between 0.35 and 1.10.

• **LIGHT TREATMENT PROCEDURE:** One eye was adjusted to correct the patients' postoperative refractive errors. Two light treatments were applied in the fellow eye to set the refraction and to induce negative values of spherical aberration. In the first adjustment, we used the adequate profile to both reduce the astigmatism and reach a value of spherical equivalent of around +0.50 D. The slight amount of residual hyperopia after the first adjustment was preferred to precompensate for the myopic shift produced by the aspheric profiles. In the second adjustment, we selected the appropriate aspheric profile to optimize the spherical aberration to the visual needs of patients for different viewing distances.

RESULTS

• **REFRACTION AND SPHERICAL ABERRATION AFTER TREATMENTS:** Table 1 shows the refractive results for all patients' eyes before treatments, and after all treatments in those eyes set for distance and after first treatment in the eyes set for near vision. The uncorrected visual acuity (UCVA) in the eyes set for distance was found to be ≥0.9, for all cases. In the fellow eye set for near vision, after the first adjustment the equivalent sphere was around +0.50 D as targeted. The final refraction and visual acuity results after aspheric light adjustment depend on the magnitude of the induced amount of spherical aberration. Table 2 shows refraction and spherical aberration data for 4 mm pupil in 2 groups of patients selected based on the amount of induced asphericity. Prior to the aspheric adjustment, the eye's spherical aberration was positive,[19] ranging from +0.02 to +0.15 μm in all subjects. Taking into account these previous values of spherical aberration, we selected the appropriate aspheric profile to customize the final net value. In Group 1 (12 patients), our aim was to increase depth of focus while maintaining a good distance VA. In this case, spherical aberration was changed from +0.06 to −0.08 μm on average, the final values ranging from −0.10 to −0.05 μm. Group 2 (5 patients) included patients requesting improved near vision. In this group, spherical aberration was modified on average from +0.09 to −0.19 μm, with a range between −0.23 and −0.13 μm. Table 2 shows the statistical differences (*P* value from *t* test) between both groups. The mean values of spherical aberration prior to the aspheric treatment were +0.06 and +0.09 μm for Group 1 and 2, respectively, but they are not statistically different (*P* value = .20). As expected, the spherical aberration after the aspheric treatment is significantly different in these groups (*P* value < .01). After the aspheric treatments, patients were myopic, around −1.00 and −1.50 D for each group. The increment of depth of focus with induced spherical aberration extends the refractive range with a similar acuity, so it is usually more difficult to select the defocus value yielding the highest VA. For this reason, we find a variability in the spherical equivalent values in both groups (*P* value = .07), from −1.75 to −0.38 D and −2.25 to −0.75 D.

• **VISUAL ACUITY FOR DIFFERENT VIEWING DISTANCES:** Table 3 and Figures 2 and 3 show both the monocular and binocular UCVA after all treatments were completed for Groups 1 and 2. As expected, in both groups (*P* value > .6) the eyes adjusted for emmetropia at distance vision have a good VA at 10 meters, on average >1.10, but VA decreases quickly at the near viewing distances. The monocular visual acuities of eyes with lower induced negative spherical aberration (Group 1) are good for far and intermediate distances, around 1.00 (Jaeger value [J]1+), but decreases to 0.71 (J2) at 40 cm and to 0.50 (J3) at 30 cm. In eyes with a higher amount of induced negative spherical aberration (Group 2), the behavior is different. At intermediate distance (60 cm) VA was 0.95 (J1+) (*P* value = .81), and for nearer distances (eg, 40 and 30 cm), VA was 0.94 (J1+) and 0.73 (J2), respectively (*P* value < .01). However, there was a reduction of VA at distance: 0.76 (*P* value < .01). Figure 4 shows the differences between both groups of eyes treated with different, targeted amounts of negative spherical aberration. In all patients, binocular summation slightly improves the binocular VA, between 0.02 and 0.09, with respect to the best monocular data. In Group 2, the combination of both eyes gives a binocular VA equal or higher than 1.0 (J1+) for all distances except at 30 cm, where VA is 0.75 (J2–J1). In Group 1, smaller amounts of negative spherical aberration produce binocular VAs at 40 cm of 0.80 (J1) and 0.57 (J3) at 30 cm. Figure 5 directly compares the binocular VA in both groups, showing higher VA at closer distances, 40 and 30 cm, in the eyes with larger induced negative spherical aberration (*P* value < .01).

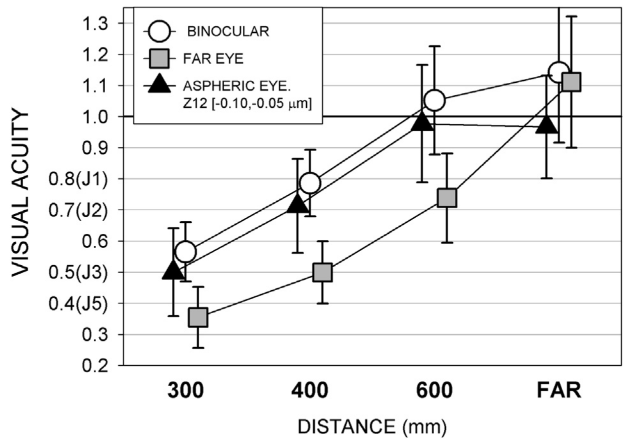

FIGURE 2. Average values of monocular and binocular uncorrected visual acuity at different distances in Group 1 of patients implanted with light-adjustable intraocular lenses. In Group 1 (12 patients), 1 eye is set for distance vision (far eye) and the fellow eye (aspheric eye) is set to obtain low values of negative ocular spherical aberration (Zernike coefficient Z12), between −0.10 and −0.05 μm for 4-mm pupil diameter. This would improve intermediate and near vision. Error bars are the standard deviation from individual measurements. Visual acuity is expressed in decimal units with the equivalent Jaeger (J) for some selected values.

DISCUSSION

AS EXPECTED, OUR RESULTS SHOW A SIGNIFICANT increase of depth of focus after the induction of negative spherical aberration. Furthermore, light-adjustable lenses allow customizing of the values of spherical aberration depending on the specific needs of each patient. We can enhance near VA by increasing the amount of negative

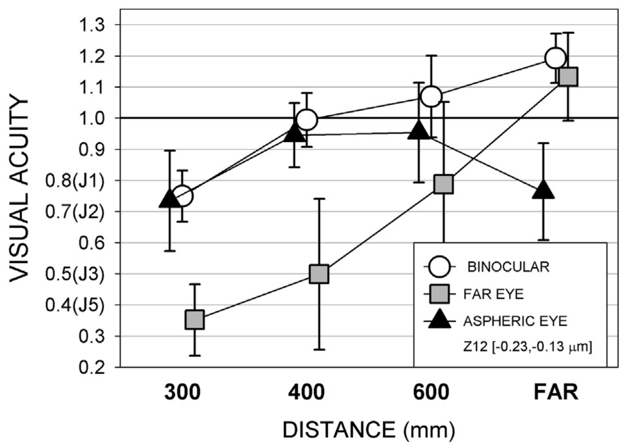

FIGURE 3. Average values of monocular and binocular uncorrected visual acuity at different distances in the Group 2 of patients implanted with light-adjustable intraocular lenses. In Group 2 (5 patients), 1 eye is set for distance vision (far eye) and the fellow eye (aspheric eye) is set to obtain high values of negative ocular spherical aberration (Z12), between −0.23 and −0.13 microns for 4-mm pupil diameter. This would improve intermediate and near vision. Error bars are the standard deviation from individual measurements. Visual acuity is expressed in decimal units with the equivalent Jaeger value (J) for some selected values.

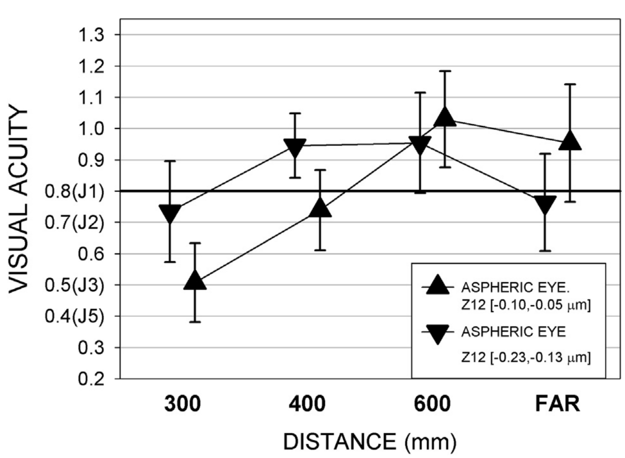

FIGURE 4. Comparison of monocular uncorrected visual acuity of eyes set with aspheric adjustments (aspheric eye) to get low, between −0.10 and −0.05 μm (referred to as Group 1 in the text), and high, between −0.23 and −0.13 μm (Group 2), values of ocular spherical aberration (Z12). Visual acuity is expressed in decimal units with the equivalent Jaeger value (J) for some selected values.

SA, although at the cost of a degradation in distance VA. This approach provides a better solution as compared with pure standard monovision. Hayashi and associates[20] studied the monocular and binocular VA in pseudophakic patients with monovision for different amounts of anisometropia. Their results show a near VA around J2 at 40 cm for additions between 1.0 and 1.5 D, similar to our outcomes in patients with low values of SA. However, distance VA in these eyes with pure myopia decreases below 0.5 while in eyes with low amounts of spherical aberration it remains over 0.9. Eyes with 2.0 D of myopia have VA around J1 at 40 cm, but distance VA falls below 0.3, while in eyes with high values of spherical aberration the VA at 40 cm is better than J1 and at 10 m ranges between 0.6 and 0.9.

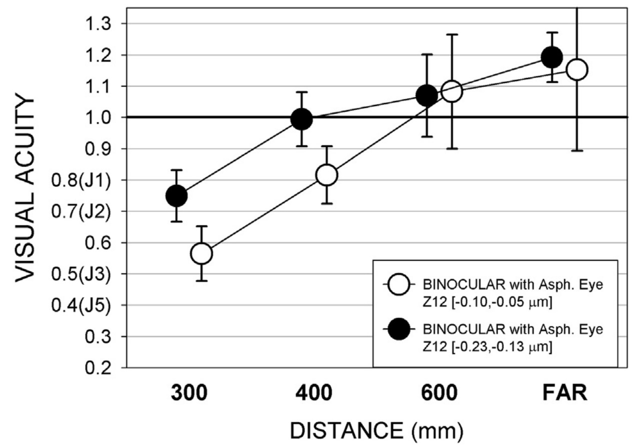

FIGURE 5. Comparison of binocular uncorrected visual acuity of Groups 1 and 2 of patients implanted with light-adjustable intraocular lenses. In both groups, 1 eye is set for distance vision, but in Group 1 the fellow eye is set to obtain low values of negative ocular spherical aberration (Z12), between −0.10 and −0.05 μm, and in Group 2 the fellow eye is set to obtain higher values of ocular spherical aberration, between −0.23 and −0.13 μm. Visual acuity is expressed in decimal units with the equivalent Jaeger value (J) for some selected values.

Although both positive and negative spherical aberration increases depth focus, we have chosen in this study to provide the eye with a net final negative spherical aberration. This provides a better performance in combination with small myopic defocus errors that can be common within our procedure.

The induction of spherical aberration could add third-order aberrations, such as coma, that could also contribute to extend depth of focus. Although centration of the light treatments was controlled during the process, we have also studied the induction of third-order aberrations induced by aspheric profiles. Figure 6 shows the difference between the root mean square (RMS) for third-order aberrations before aspheric adjustments and after all light treatments as a function of the amount of induced spherical aberration. In most cases, there was an increment in the magnitude of third-order aberrations, which could be produced by the typical decentration of the IOL with respect to the natural pupil.[21] However, we did not find a significant correlation ($R^2 = 0.05$) between the induced SA and third-order aberrations. This suggests that the main contribution to the measured extended depth of focus was the induced spherical aberration.

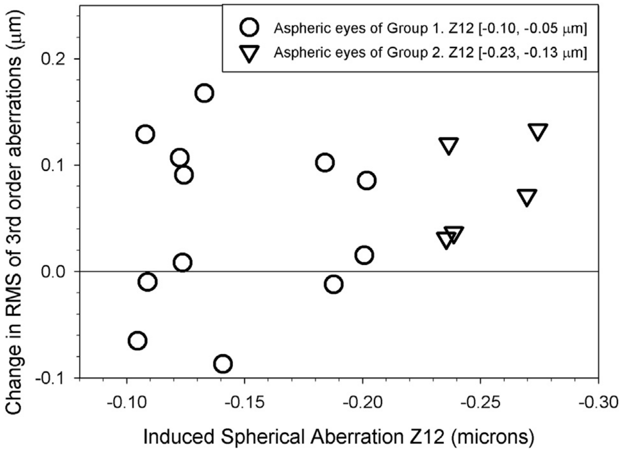

FIGURE 6. Relationship between the induced spherical aberration (Z12) and the root mean square (RMS) of third-order aberrations after all light treatments are completed. Different symbols refer to the 2 considered groups of patients: Group 1 for eyes with low values of negative spherical aberration, between −0.10 and −0.05 μm, and Group 2 for eyes with higher values, between −0.23 and −0.13 μm.

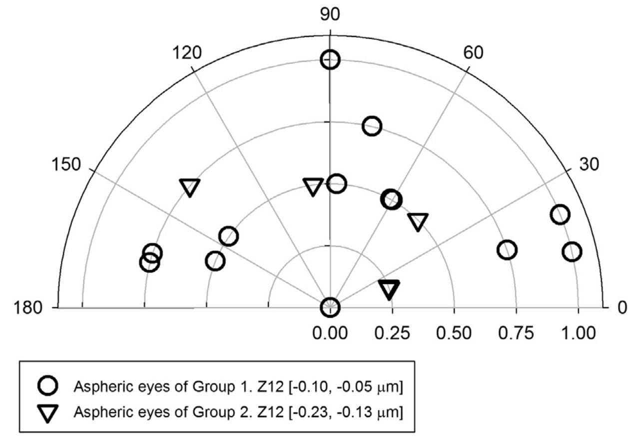

FIGURE 7. Distribution of positive cylinder (magnitude and axis) after light treatments in all patients. Different symbols refer to the 2 considered groups: Group 1 for eyes with low values of negative spherical aberration, between −0.10 and −0.05 μm, and Group 2 for eyes with higher values, between −0.23 and −0.13 μm.

In addition, induced astigmatism after cataract surgery has been also suggested to increase depth of focus at the cost of a reduced vision at distance.[22] In our study, owing to the nature of the adjustable lens technology, cylinder errors were reasonably well corrected and randomly distributed among the patients. Figure 7 shows the positive cylinder values after adjustment and lock-in treatments in each patient in a polar representation. Since there are no differences, either in values or in orientation, in astigmatism between both groups, the reported depth of focus is consistent with that mainly produced by the induced spherical aberration.

Another important advantage of this approach using light-adjustable lenses is the possibility of full customization of the induced SA. One option will be to decide in advance for each patient the desired value of spherical aberration for a compromise of vision at all distances. This can be achieved using instruments based on adaptive optics vision analyzers.[23,24]

In conclusion, we demonstrated that light-adjustable intraocular lenses can be successfully used to induce targeted amounts of negative spherical aberration to increase a patient's depth of focus. Refraction and spherical aberration should be carefully measured previously to select the optimum light profiles to obtain a vision quality customized at all distances. Small values of negative spherical aberration (ie, −0.05 to −0.10 μm) maintain good visual quality for far and intermediate distances, but visual acuity decreases at very close distances. Higher values of negative SA (ie, −0.13 to −0.23 μm) improve near vision but deteriorate far vision. In this way, customized vision for a patient's different viewing requirements can be achieved.

The binocular combination of 1 eye with negative spherical aberration and the other eye adjusted for distance-emmetropia guarantees excellent vision quality for far and intermediate distances, with VA at closer distances dependent on the magnitude of induced asphericity. Although binocular summation slightly improves vision quality at all distances, large amounts of negative spherical aberration in 1 of the eyes increases the binocular rivalry and the possibility of suppression. Further studies are being conducted to predict in advance the best vision quality to customize the amounts of induced spherical aberration and the different binocular combinations for each patient.

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REFERENCES

1. Canovas C, Artal P. Customized eye models for determining optimized intraocular lenses power. *Biomed Opt Express* 2011; 2(6):1649–1662.
2. Narváez J, Zimmerman G, Stulting RD, Chang DH. Accuracy of intraocular lens power prediction using the Hoffer Q, Holladay 1, Holladay 2, and SRK/T formulas. *J Cataract Refract Surg* 2006;32(12):2050–2053.
3. Wang JK, Hu CY, Chang SW. Intraocular lens power calculation using the IOLMaster and various formulas in eyes with long axial length. *J Cataract Refract Surg* 2008;34(2): 262–264.
4. Haigis W. Intraocular lens calculation after refractive surgery for myopia: Haigis-L formula. *J Cataract Refract Surg* 2008; 34(10):1658–1663.
5. Barequet IS, Yu E, Vitale S, Cassard S, Azar DT, Stark WJ. Astigmatism outcomes of horizontal temporal versus nasal clear corneal incision cataract surgery. *J Cataract Refract Surg* 2004;30(2):418–423.
6. Guirao A, Tejedor J, Artal P. Corneal aberrations before and after small-incision cataract surgery. *Invest Ophthalmol Vis Sci* 2004;45(12):4312–4319.
7. Schwartz DM. Light-adjustable lens. *Trans Am Ophthalmol Soc* 2003;101:417–436.
8. Schwartz DM, Sandstedt CA, Chang SH, Kornfield JA, Grubbs RH. Light-adjustable lens: development of in vitro nomograms. *Trans Am Ophthalmol Soc* 2004;102:67–72 [discussion: 72-74].
9. Chayet A, Sandstedt C, Chang S, et al. Correction of myopia after cataract surgery with light-adjustable lens. *Ophthalmology* 2009;116(8):1432–1435.
10. Chayet A, Sandstedt C, Chang S, Rhee P, Tsuchiyama B, Schwartz D. Correction of residual hyperopia after cataract surgery using the light adjustable lens technology. *Am J Ophthalmol* 2009;147(3):392–397.
11. Hengerer FH, Dick HB, Conrad-Hengerer I. Clinical evaluation of an ultraviolet light adjustable intraocular lens implanted after cataract removal: eighteen months follow-up. *Ophthalmology* 2011;118(12):2382–2388.
12. Chayet A, Sandstedt C, Chang S, et al. Use of the light-adjustable lens to correct astigmatism after cataract surgery. *Br J Ophthalmol* 2010;94(6):690–692.
13. Sandstedt CA, Chang SH, Grubbs RH, Schwartz DM. Light-adjustable lens: customizing correction for multifocality and higher-order aberrations. *Trans Am Ophthalmol Soc* 2006; 104:29–39.
14. Prieto PM, Vargas-Martín F, Goeltz S, Artal P. Analysis of the performance of the Hartmann-Shack sensor in the human eye. *J Opt Soc Am A* 2000;17(8):1388–1398.
15. Guirao A, Artal P. Corneal wave aberration from videokeratography: accuracy and limitations of the procedure. *J Opt Soc Am A* 2000;17(6):955–965.
16. Artal P, Guirao A, Berrio E, Williams DR. Compensation of corneal aberrations by internal optics in the human eye. *J Vis* 2001;1(1):1–8.
17. Artal P, Benito A, Tabernero J. The human eye is an example of robust optical design. *J Vis* 2006;6(1):1–7.
18. American National Standards Institute (ANSI). American National Standard for Ophthalmics - Methods for reporting optical aberrations of the eye (ANSI Z80.28-2004). Washington, DC: ANSI; 2004.
19. Artal P, Berrio E, Guirao A, Piers P. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *J Opt Soc Am A* 2002;19(1):137–143.
20. Hayashi K, Yoshida M, Manabe S, Hayashi H. Optimal amount of anisometropia for pseudophakic monovision. *J Refract Surg* 2011;27(5):332–338.
21. McKelvie J, McArdle B, McGhee C. The influence of tilt, decentration, and pupil size on the higher-order aberration profile of aspheric intraocular lenses. *Ophthalmology* 2011; 118(9):1724–1731.
22. Hayashi K, Hayashi H, Nakao F, Hayashi F. Influence of astigmatism on multifocal and monofocal intraocular lenses. *Am J Ophthalmol* 2000;130(4):477–482.
23. Fernández EJ, Manzanera S, Piers P, Artal P. Adaptive optics visual simulator. *J Refract Surg* 2002;18(5):S634–S638.
24. Schwarz C, Prieto P, Fernández EJ, Artal P. Binocular adaptive optics vision analyzer with full control over the complex pupil functions. *Opt Letters* 2011;36(24):47779–47781.