Binocular Visual Performance After LASIK

José Ramón Jiménez, PhD; Cesar Villa, MD; Rosario González Anera, PhD; Ramón Gutiérrez, PhD; Luis Jiménez del Barco, PhD

ABSTRACT

PURPOSE: To analyze binocular visual function after LASIK.

METHODS: Eye aberrometry and corneal topography was obtained for both eyes in 68 patients (136 eyes). To evaluate visual performance, monocular and binocular contrast sensitivity function and disturbance index for quantifying halos were measured. Tests were performed under mesopic conditions.

RESULTS: Binocular summation and disturbance index diminished significantly ($P<.0001$) after LASIK with increasing interocular differences in corneal and eye aberrations. Binocular visual deterioration was greater than monocular deterioration for contrast sensitivity function and disturbance index.

CONCLUSIONS: Binocular function deteriorates more than monocular function after LASIK. This deterioration increases as the interocular differences in aberrations and corneal shape increase. Improvements in ablation algorithms should minimize these interocular differences. [*J Refract Surg*. 2006;22:679-688.]

Various studies have demonstrated that corneal and eye aberrations[1-4] as well as night vision disturbances[5,6] can increase after refractive surgery, while contrast sensitivity function can diminish after refractive surgery.[7-9] In general, studies on postoperative deterioration have concerned only monocular function, analyzing the results for each eye, with postoperative binocular function rarely being considered.[10]

Interocular differences are known to affect visual performance.[11-16] Jimenez et al[16] demonstrated binocular summation measured by contrast sensitivity function in emmetropic subjects is reduced when the asphericities of the cornea differ. After surgery, pronounced changes such as an increase in aberrations and differences in corneal shape[1,2,5,8,17,18] occur in the eye; these changes partially explain the monocular deterioration in contrast sensitivity.[7] In the binocular case, a reduction in postoperative binocular summation can be expected when large interocular differences appear in eye aberrations and corneal shape.

In this study, we analyzed the role of interocular differences in aberrations and corneal shape on binocular visual function. Although many different visual functions can be used to evaluate binocular vision performance, this study examined contrast sensitivity function and the disturbance index for halos (a measure for quantifying night vision disturbances). Constrast sensitivity is a common and useful function to

---

From the Laboratorio de Ciencias de la Visión y Aplicaciones, Departamento de Óptica, Facultad de Ciencias, Universidad de Granada, Granada (Jiménez, Anera, Jiménez del Barco); the Clínica de Oftalmología Novovisión, Paseo de la Castellana, Madrid (Villa); and the Departamento de Oftalmología, Universidad de Murcia, Murcia (Gutiérrez), Spain.

This research has been supported in part by the Ministerio de Ciencia y Tecnología, grant no. BFM 2003-01492 (Spain).

The authors have no proprietary interest in the materials presented herein.

The authors thank David Nesbitt for translating the text into English.

Correspondence: José Ramón Jiménez, PhD, Laboratorio de Ciencias de la Visión y Aplicaciones, Departamento de Óptica, Edificio Mecenas, Universidad de Granada, Granada 18071, Spain. Tel: 34 958246165; Fax: 34 958248533; E-mail: jrjimene@ugr.es

Received: December 14, 2005

Accepted: February 15, 2006

evaluate spatial sensitivity. In addition, under normal conditions, binocular contrast sensitivity function is greater than monocular contrast sensitivity function, and therefore the comparison of pre- and postoperative binocular and monocular data can indicate possible deterioration of binocular visual function and whether it is greater than deterioration of monocular function. Halos constitute one of the night vision disturbances most frequently cited by patients who have undergone refractive surgery. Quantitative measurements of night vision disturbances are of great use in evaluating the surgical process and avoid the high subjectivity of questionnaires. For this study, we used a halometer[6] to measure and quantify halo effects. As with contrast sensitivity function, experimental data on the disturbance index will yield information on binocular and monocular postoperative deterioration. The lighting conditions used in this study were mesopic, a condition in which decreased contrast sensitivity function and the appearance of halos is more usual.

PATIENTS AND METHODS

This study included a total of 136 eyes in 68 patients who underwent LASIK. Informed consent was obtained from all patients in accordance with the Helsinki Declaration. Surgery was performed in a refractive surgery clinic with a noncustomized procedure using the VISX Star S2 (VISX Inc, Santa Clara, Calif). Patient age ranged from 20 to 42 years, with 80% between 21 and 26 years. Mean (±standard deviation [SD]) preoperative spherical equivalent refraction was -4.20 ± 2.10 diopters (D) (range: -1.00 to -7.50 D). The optical zone was 6 mm.

All patients met the following conditions: after 3 months, they were satisfied with their outcome and no longer used any form of optical correction; mean postoperative spherical refractive error did not exceed 0.5 D (to avoid the influence of defocusing in contrast sensitivity function[8]); and postoperative visual acuity was roughly equal (either higher or one Snellen line lower) to preoperative best spectacle-corrected visual acuity (BSCVA). No patient had a pre-existing condition (eg, glaucoma, corneal or neuro-ophthalmic diseases, or cataracts) that might affect contrast sensitivity.

EYE ABERRATIONS AND CORNEAL TOPOGRAPHY

Pre- and postoperative data on corneal shape were obtained with the Orbscan II (Bausch & Lomb, Rochester, NY). Eye aberrations were measured with Zywave (version 3.2, Bausch & Lomb), based on the Hartmann-Shack sensor system. No dilatation was used for measuring aberrations. Orbscan and aberrometer data were used to compile information on aberrations and corneal shape using Vol-Pro software (Sarver & Associates, Carbondale, Ill). The effects of eye aberrations were computed with the root-mean-square (RMS) parameter (from third-order coefficients) and the coefficient for spherical aberration.[1,2,4]

CONTRAST SENSITIVITY FUNCTION

The contrast sensitivity function test was conducted using Vision Works software (Vision Research Graphics, Durham, NH). The monitor was calibrated with a spectroradiometer PR-704 (Photo Research Inc, Chatsworth, Calif) according to the instruction given by Vision Works. The minimum contrast sensitivity increment was 4%. The frequencies tested were: 1.5, 3.1, 6.1, 9.8, 14.2, and 18 cycles per degree (cpd). The test distance was 6 m.

Contrast sensitivity function was determined based on the limits method.[8,16] At the beginning of each session, a 2-minute dark adaptation period was used to minimize the influence of adaptation at previous illumination levels. Then, for a fixed spatial frequency, patients began with the lowest contrast value available, the contrast increasing until patients could indicate the grating. This procedure was repeated three times. The contrast threshold was the average of the three contrasts perceived by patients.[8,16] For the contrast sensitivity function, contrast sensitivity was computed as the reciprocal of the contrast threshold. Binocular as well as monocular contrast sensitivity function was determined before (best-corrected) and after surgery without correction.

DISTURBANCE INDEX FOR HALOS

A halometer was used to measure halo effect. This device, which has been analyzed extensively,[6] enables the quantification of this phenomenon, providing a disturbance index. The halometer consists basically of a board with electronic components within a methacrylate box connected to a personal computer. Tested with normal subjects and patients after LASIK, this apparatus has proven sufficiently sensitive[6] in patients who underwent surgery. Patients seated in front of the device view a black screen with different holes that permit the exit of light from the central and peripheral light emitting diodes arranged in 12 radial lines (Fig 1). The central high-intensity light (an angular size of 0.34°) serves also for fixation of the patient's gaze. The task of the patient was to discriminate the lateral luminous spots (0.06°) with respect to the central spot. This test was chosen because patients who see halos around a central source should have greater difficulty in discriminating peripheral lights surrounding the central source.[6]

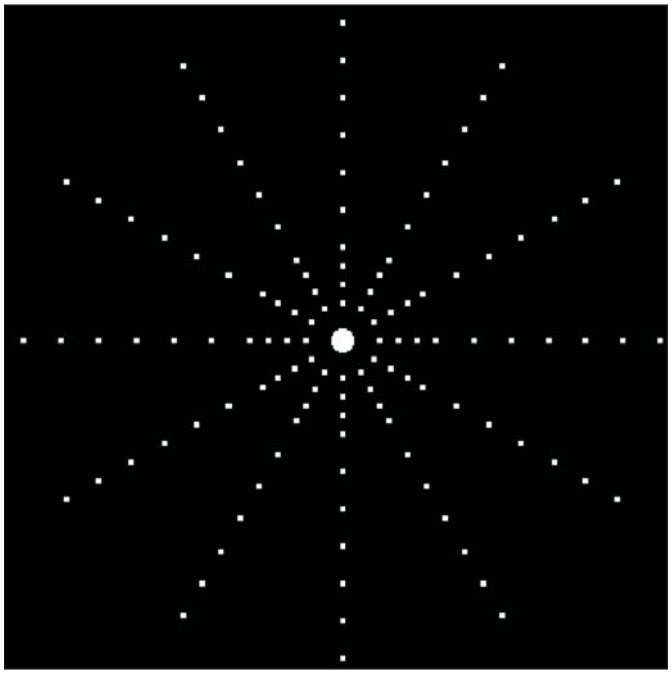

Figure 1. Patients seated in front of the halometer view a black screen with holes arranged in 12 radial lines around a central high-intensity light source.

After an adaptation period (3 minutes of dark followed by 1 minute of central stimulus), patients were presented randomly with stimuli from the 12 radial lines. On detecting peripheral spots, patients press a remote-control button, and this information is stored for subsequent treatment and to calculate the disturbance index. This index is determined as the quotient of the area of the spots not detected by the patient divided by the total area presented to the patient, and this value is expressed as a percentage. False-alarm analysis was made previously. As the disturbance index increases, the discrimination capacity decreases, indicating a greater influence of halos. After undergoing an initial trial session, all patients underwent three sessions, and the disturbance index was calculated as the average of the three sessions. Measurements were taken before (best-corrected) and after LASIK.

LIGHTING CONDITIONS AND BINOCULAR-SUMMATION COMPUTATION

Pupil size must be in the mesopic or scotopic range[19] for a night vision disturbance test and for testing the influence of aberrations in visual performance. The halometer test guarantees this condition[6]; for the contrast sensitivity function test, the average luminance level of the cathode-ray tube monitor was 8 cd/m^2, a value within the mesopic range.[19] Using a Colvard pupillometer (Oasis Medical, Glendora, Calif), patients' pre- and postoperative pupil size was measured at the average luminance level of the tests. Pupil size during both tests ranged from 5.1 to 6.1 mm. For unifying aberrometric data, all computations in RMS, spherical aberrations, and corneal shape were computed for a 5-mm pupil size using the Vol-Pro software.

TABLE 1

Definitions of Metrics Used in This Study

Disturbance index for halos	Area of spots not detected/Total area of the test
Binocular summation for CSF	Binocular CSF/Mean monocular CSF
Binocular summation for disturbance index	Mean monocular index/ Binocular index
Postoperative deterioration for CSF	Postoperative CSF/Preoperative best-corrected CSF

CSF = contrast sensitivity function

For each condition (binocular and monocular), the possible deterioration due to surgery was calculated, comparing preoperative best-corrected data with postoperative data. For contrast sensitivity function, to compare postoperative binocular with monocular data, binocular summation was used. There are different alternatives[20-22] to compute binocular summation. In this study, for each patient under each condition, we calculated the average of the contrast sensitivity function data for all of the frequencies tested, although we also made an analysis as a function of the spatial frequency. For each patient, binocular summation was calculated by dividing the binocular contrast sensitivity function by the mean of the two monocular contrast sensitivity function data.[20-22] A different alternative[20] is to divide the binocular contrast sensitivity function by the "best eye" contrast sensitivity function; results also were computed in this way. The different metrics used in this study are defined in Table 1.

In the case of the halometer, as the discrimination capacity increases, the disturbance index decreases. Thus, to compare monocular with binocular data, we computed the quotient between the mean of the monocular-disturbance indexes with the disturbance index computed binocularly. As the discrimination capacity under normal conditions is better binocularly than monocularly, a value >1.0 is expected for all patients. A value close to 1.0 would indicate the monocular and binocular discrimination capacity are similar. For the halometer test, we will continue to call this quotient "binocular summation" as it represents the same concept as for the test of the contrast sensitivity function and other psycho-

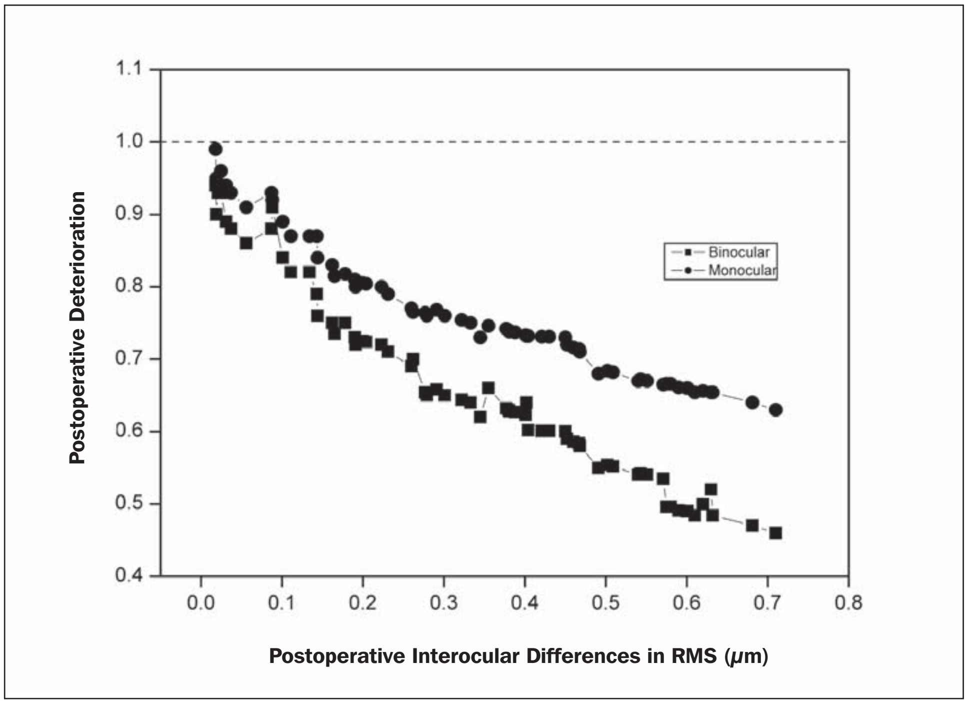

Figure 2. Graph depicts deterioration of contrast sensitivity function after LASIK: monocular and binocular case as a function of the postoperative interocular differences in eye aberrations (root-mean-square [RMS] from third-order coefficients in microns). Deterioration for contrast sensitivity is defined as the ratio between postoperative CSF and preoperative best-corrected CSF.

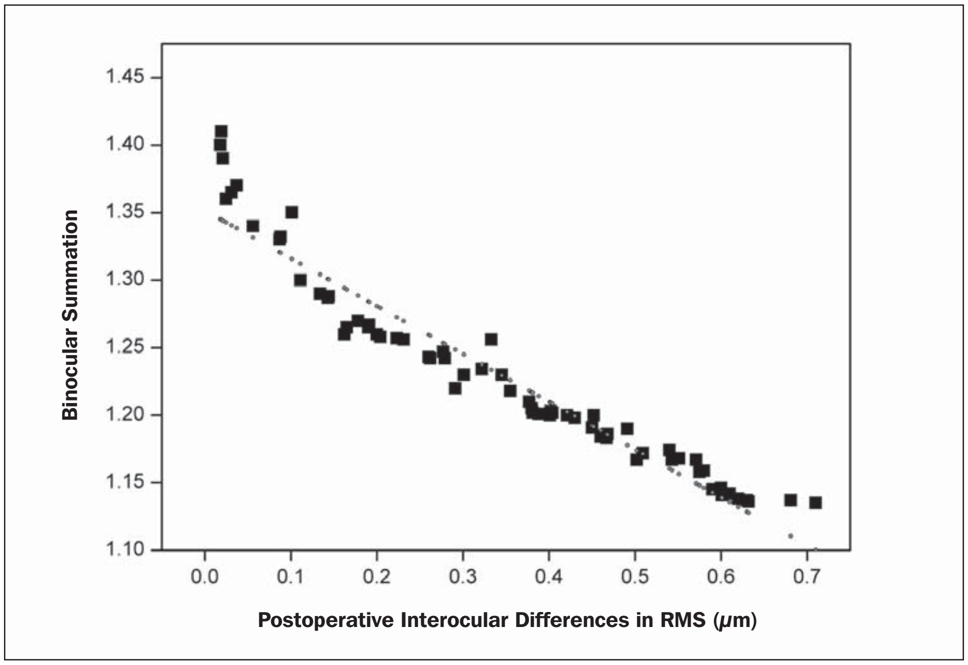

Figure 3. Graph depicts binocular summation for contrast sensitivity as a function of the postoperative interocular differences in eye aberrations (root-mean-square [RMS] from third-order coefficients in microns).

physical functions[11] used for comparing binocular with monocular vision. To compare pre- and postoperative data, we divided the preoperative (best-corrected) disturbance index by the postoperative index, for which a value <1.0 would indicate that the discrimination capacity had deteriorated after surgery.

RESULTS

Binocular and monocular postoperative deterioration (postoperative values divided by the best-corrected preoperative contrast sensitivity function values) are shown in Figure 2. There was a significant deterioration with increasing postoperative interocular differences in eye aberrations (RMS from third-order coefficients) ($P<.0001$). According to different experimental results,[1,2] monocular deterioration was expected; the novelty is that this deterioration also occurs binocularly and is greater than the monocular deterioration, demonstrating that binocular vision worsens more than monocular and that this effect is greater as post-

TABLE 2

Comparison of Pre- and Postoperative Mean Spherical Equivalent Refraction, Root-Mean-Square, and Binocular and Monocular Contrast Sensitivity Function

	Preoperative	Postoperative
Mean spherical equivalent (D)	−4.22±1.90	−0.03±0.31
Range	−1.0 to −7.5	0.5 to −0.5
Root-mean-square (5 mm) (μm)*	0.342±0.102	0.616±0.157
Mean contrast sensitivity function†		
Binocular	91.4±76.8‡	60.3±50.7
Monocular	59.4±42.3‡	45.6±38.2

*From third order.
†Mean for all frequencies.
‡Best-corrected.

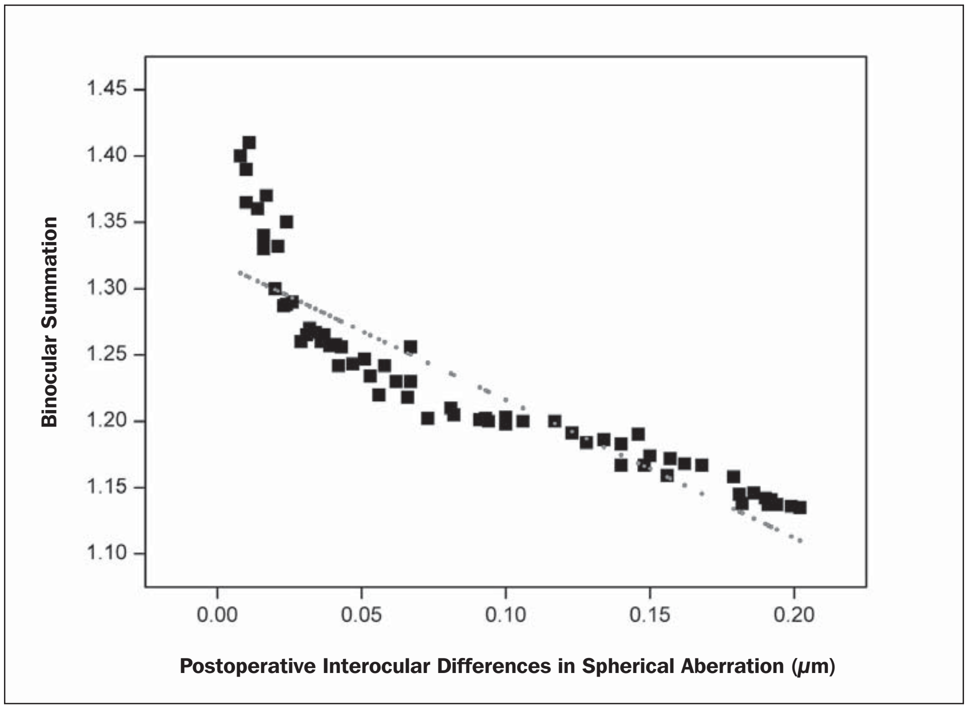

Figure 4. Graph depicts binocular summation for contrast sensitivity as a function of the postoperative interocular differences (microns) in eye spherical aberration (Z_4^0).

operative interocular differences in RMS increase. This finding is important because under normal conditions, vision is binocular. In monocular vision, a significant dependence ($P<.0001$) was found with the interocular differences in eye aberrations, but the dependence was more pronounced in the binocular case, reflecting a stronger role of these differences in the binocular case.

This result also appeared in terms of postoperative binocular summation. Figure 3 presents the postoperative binocular summation as a function of the postoperative interocular differences in eye aberrations (RMS parameter). Summation decreased as interocular differences increased. The high correlation coefficient found ($r^2=0.86$, $P<.0001$) confirms this trend. Table 2 shows the average pre- and postoperative data for spherical equivalent refractive error, RMS (from third-order coefficients), and contrast sensitivity function.

One of the most relevant aberrations is spherical aberration. This is important in practical surgery because studies have demonstrated a notable increase after surgery.[1,2] Figure 4 shows the postoperative binocular summation as a function of the postoperative interocular differences in spherical aberration (Z_4^0, spherical coefficient). The same trend as with eye aberrations was found, with a significant decrease in spherical aberration occurring as interocular differences increased ($r^2=0.81$, $P<.0001$). It should be pointed out in reference to Figures 3 and 4 that in the narrow range of low interocular differences

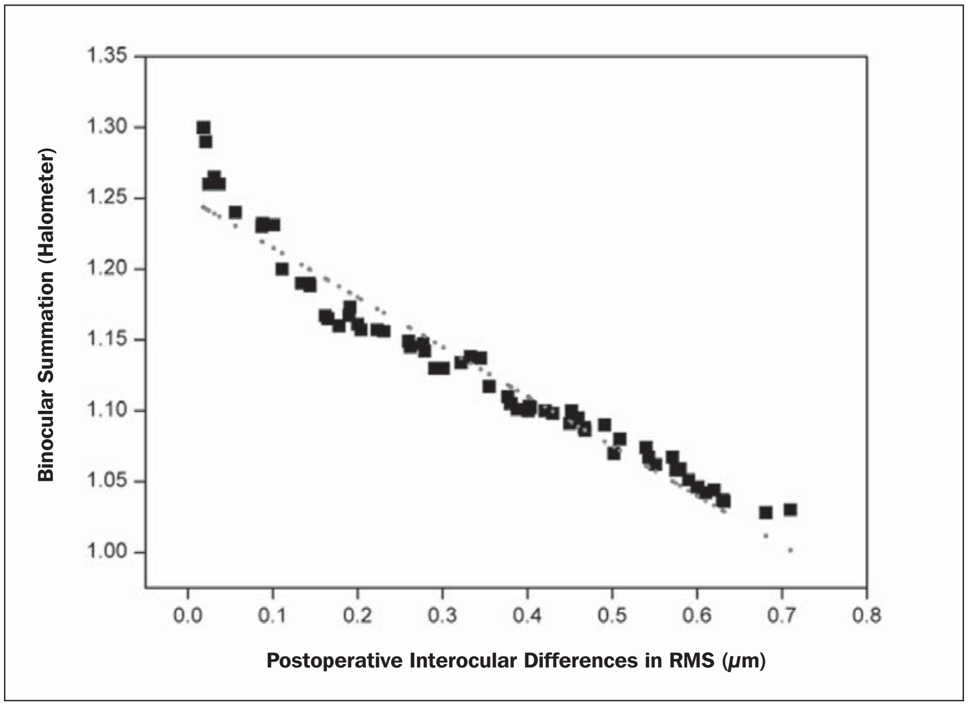

Figure 5. Graph depicts binocular summation as a function of the postoperative interocular differences in eye aberrations (root-mean-square [RMS] from third-order coefficients in microns) for the halometer.

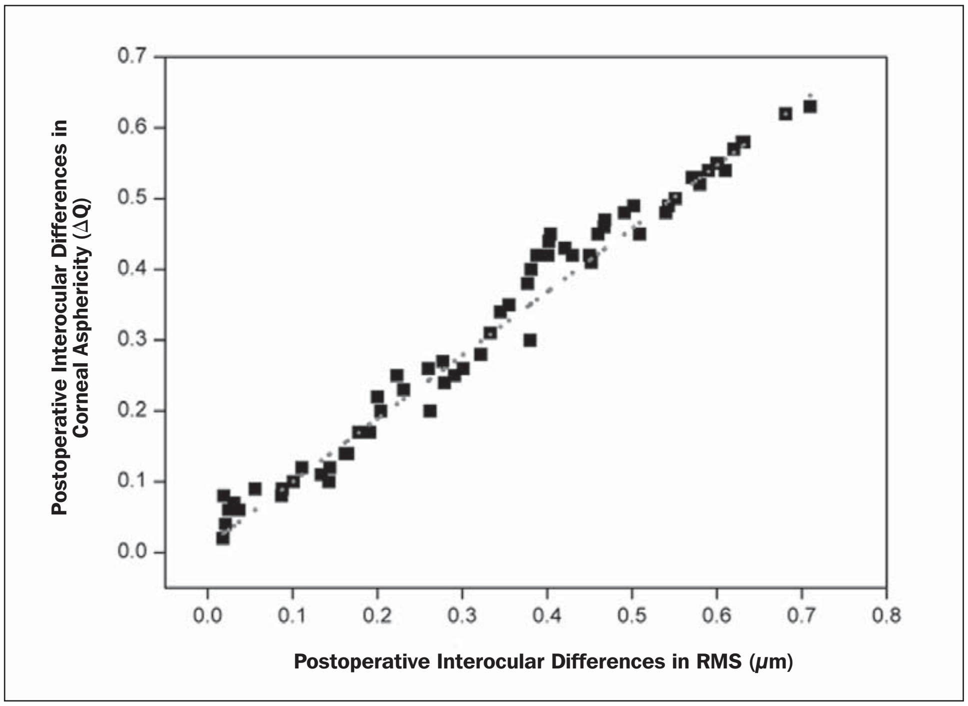

Figure 6. Graph depicts postoperative interocular differences in corneal asphericity (ΔQ) as a function of the postoperative interocular differences in eye aberrations (root-mean-square [RMS] from third-order coefficients in microns).

(≤0.05 μm), there was large variability in binocular summation.

Figure 5 presents halometer results, which were similar to the contrast sensitivity function results. The results reflect a deterioration in binocular summation (r^2=0.91, $P<.0001$) as the postoperative interocular differences increased, demonstrating that a binocular deterioration higher than monocular also is detected with a different visual function—in this case, the disturbance index that measured the discrimination capacity. The average preoperative (best-corrected) disturbance index in the monocular case was 28.2±2.4, which increased significantly to 51.0±2.8 ($P<.0001$) postoperatively. Therefore, we confirmed the results found with this device,[6] in which this apparatus can quantitatively detect the effect of halos in visual perception and the deterioration in discrimination after LASIK.

Figure 6 shows postoperative interocular differenc-

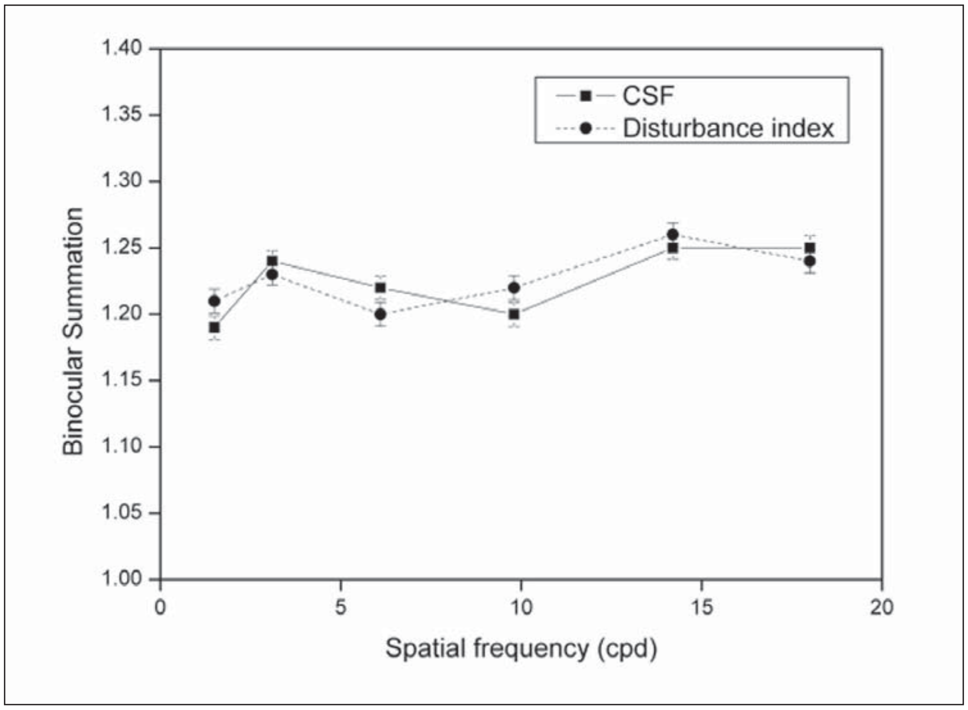

Figure 7. Graph depicts average binocular summation for contrast sensitivity function (CSF) and disturbance index as a function of spatial frequency (cpd). Data include standard errors.

es in corneal asphericity (ΔQ) as a function of the postoperative interocular difference in RMS aberrations. We found a highly significant correlation (r^2=0.92, P<.0001), this result being explained by the fact that the parameter corneal asphericity provides an average of corneal shape. It is well known that variations in this parameter induce proportional variations in eye aberrations[19]; therefore, the greater the interocular differences in corneal shape, the higher the interocular differences in aberrations.

The selective deterioration of postoperative LASIK for spatial frequency is well known.[7-9,23-25] This deterioration has been found only monocularly, so we computed the postoperative binocular summation as a function of the spatial frequency. Figure 7 shows the average binocular summation for contrast sensitivity function and disturbance index as a function of the spatial frequency. According to an analysis of variance, the means did not differ significantly (P>.05 for both cases).

DISCUSSION

For many visual functions, including contrast sensitivity function, the binocular system is more efficient than the monocular system,[11,20-22,26,27] with a binocular summation greater than unity. An analysis of Figures 3 and 4 shows that for all patients, the postoperative binocular system continued to be more effective than the monocular one, as the binocular summation was >1.0, as might be expected. The point is that this effectiveness decreases as interocular differences increase, showing that interocular differences (in this case, eye aberrations) play an important role in visual function. The origin of binocular summation,[26-28] if neural or probability, depends on the value reached by the binocular summation. A binocular summation value of 1.2 indicates that the superior binocular performance is due only to a probabilistic origin[27] (probability summation). According to the decision model of Campbell and Green[26] for contrast-threshold experiments, a value of 1.4 indicates some interocular excitatory interaction (neural summation). From Figure 3, we observe that from approximately 0.4 µm, the influence of interocular differences is of such magnitude that binocular summation diminishes to the level of probability summation.

Concerning corneal aberrations, the same results are expected, as the change in eye aberrations are due primarily to the change in the anterior surface of the cornea, although changes also are detected in the posterior surface. This has been confirmed by different authors.[1,2] Computing corneal aberrations, we find a significant correlation with increasing interocular differences in RMS and spherical corneal aberrations (r^2=0.8 and r^2=0.81, respectively, P<.0001), drawing the same conclusions as for RMS and spherical eye aberrations.

It would be informative to study the possible clinical implications of this postoperative decrease in binocular contrast sensitivity function. We found the average percentage of contrast sensitivity function improvement of the binocular system with respect to the monocular was 54% (binocular summation 1.54) before surgery, decreasing to 26% after surgery (an average loss of 28% in contrast sensitivity function). For 31 patients, the loss was >30%; this percentage was higher than the majority of the contrast sensitivity increments that can be found in the test we used. For example, for the frequency of 6 cpd, all of the contrast sensitivity increments were <20%. We also can compare these values to the improvements expected with customized corneal ablation. Experimental results[29] show contrast sensitivity function improvements in the case of total monochromatic corrections did not exceed 80% improvement in the contrast sensitivity function up to 10 cpd. Therefore, the losses in binocular contrast sensitivity function reflected in our results (an average of approximately 30%) are important for taking binocular function into account in future improvements of refractive surgery.

We also computed binocular summation dividing the binocular contrast sensitivity function by the "best eye" contrast sensitivity function.[20] The results showed the same trend: a decreasing binocular summation as the postoperative interocular differences in eye aberrations increased, obtaining a high correlation coefficient (r^2=0.83, P<.0001 for contrast sensitivity function and r^2=0.86, P<.0001 for disturbance index).

Results concerning postoperative interocular differences in corneal asphericity (see Fig 6) agree with those reported by other authors.[16] For emmetropic subjects, high interocular differences in corneal asphericity diminished the binocular summation for the contrast sensitivity function, whereas when the interocular differences in corneal asphericity were low, the loss in binocular summation was not significant.

We should note the findings of this study were obtained with a laser platform that uses a noncustomized algorithm. Customized algorithms[30] seem to provide better contrast sensitivity outcomes than conventional LASIK. We have no data on interocular differences with customized platforms. If customized ablation also succeeds in minimizing interocular differences in eye aberrations and corneal shape, better binocular vision performance would be expected.

Concerning the dependence of binocular summation on spatial frequency, we found the dependence on spatial frequency monocularly was not maintained when considering the binocular summation parameter (see Fig 7). These results agree with those of previous reports that show no spatial-frequency dependence for binocular summation in normal subjects.[16,26]

We should not rule out that in the decline of binocular summation in postoperative patients with high interocular differences in aberrations, other factors may have had an influence, such as microstriae[31] after LASIK, which have demonstrated a certain influence of the monocular contrast sensitivity function. The influence of age[32] could not be significantly analyzed in this study given the age distribution of the patients. Also, different authors[10,33,34] have investigated a possible correlation of pupil size before and after surgery with respect to the deterioration of visual quality. In our case, we found no correlation (P>.05) between the binocular-summation data and pupil size before and after surgery, which is in agreement with the results reported by other authors.[33] In any case, it should be taken into account that on determining the contrast sensitivity function and the disturbance index binocularly, the pupil-size data are lower in the binocular case,[10,35] thereby minimizing the effects of the aberrations in the binocular case. The results of Campbell and Green[26] for threshold-contrast experiments showed binocular-summation data were slightly lower in the case of the artificial pupil (1.44) with respect to a natural one (1.43). For other visual functions, such as visual reaction time,[35] this decline also was detected in the case of the artificial pupil. In any event, threshold-contrast experiments[26] show that quantitatively, the influence is minor and does not account for all of the binocular summation.

One explanation for the role of interocular differences in visual function is that some binocular aspects, such as fusion, stereopsis, and binocular summation, depend on the spatial distribution of the images on the retina,[36-38] with these aspects being more effective when the content in spatial frequency between the two images is similar. For example, Blake and Levinson,[36] measuring contrast thresholds with differing spatial content in both images, found lower binocular summation. In our case, when the aberrations differ, the distribution of spatial frequency on the retina varies between the two eyes,[19] with this difference in the spatial distribution of the images augmenting as the difference in aberrations (or corneal shape) grows. In earlier studies,[39,40] we have shown that an asphericity change of ΔQ=0.1 generates a significant difference in the spatial distribution of the images on the retina. Therefore, when large interocular differences in aberrations are generated, a reduction in binocular summation could be expected; these results are consistent with those of other authors who have demonstrated interocular differences may play an important role in binocular vision.[11-16]

It would be useful to determine the reason why high interocular differences in corneal asphericity arise after surgery. Some authors have shown that the use of the paraxial Munnerlyn formula partially explains[8,41,42] the notable increase in aberrations and corneal asphericity in myopic patients after surgery. In any case, postoperative changes in aberrations and corneal shape cannot be totally explained[41,42] by the Munnerlyn formula, as these may be due to other factors (eg, decentration, type of laser, optical role of the flap, wound healing, and biomechanical effects[43]). All of these factors can result in large interocular differences for some patients, as the influence of these factors can prove different in each ablation. This has been experimentally confirmed with previous results[8] that have demonstrated some patients having similar initial ametropia and corneal shape in both eyes show large and significant interocular differences in corneal shape after surgery.

Ablation algorithms are founded on monocular visual function without considering binocular function. The results of this study indicate the expected results at the monocular level can lose effectiveness on being evaluated binocularly if interocular differences in eye aberrations and corneal shape arise. Therefore, a laser platform should achieve a more accurate prediction for postoperative corneal shape,[44] this being decisive in the design of new ablation algorithms. For example, a calibration procedure including correction factors from real and expected corneal shape could minimize these differences in eyes, promoting better binocular and monocular visual performance.

Our findings show a significant decline in binocular summation measured by the contrast sensitivity function and discrimination capacity around lights under mesopic conditions. This deterioration increases as the interocular differences in spherical and RMS aberrations and corneal shape increase. Binocular function deteriorates even more than monocular function. These findings indicate future improvements of ablation algorithms should analyze and minimize interocular differences in aberrations and corneal shape; otherwise, possible monocular improvements could be canceled by binocular interaction under normal viewing conditions.

REFERENCES

1. Marcos S. Aberrations and visual performance following standard laser vision correction. *J Refract Surg.* 2001;17:S596-S601.
2. Moreno-Barriuso E, Lloves JM, Marcos S, Navarro R, Llorente L, Barbero S. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. *Invest Ophthalmol Vis Sci.* 2001;42:1396-1403.
3. Oshika T, Klyce SD, Applegate RA, Howland HC, El Danasoury MA. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. *Am J Ophthalmol.* 1999;127:1-7.
4. Applegate RA, Hilmantel G, Howland HC, Tu EY, Starck T, Zayac EJ. Corneal first surface optical aberrations and visual performance. *J Refract Surg.* 2000;16:507-514.
5. Holladay JT, Dudeja DR, Chang J. Functional vision and corneal changes after laser in situ keratomileusis determined by contrast sensitivity, glare testing, and corneal topography. *J Cataract Refract Surg.* 1999;25:663-669.
6. Gutierrez R, Jimenez JR, Villa C, Valverde JA, Anera RG. Simple device for quantifying the influence of halos after LASIK surgery. *J Biomed Opt.* 2003;8:663-667.
7. Montes-Mico R, Espana E, Menezo JL. Mesopic contrast sensitivity function after laser in situ keratomileusis. *J Refract Surg.* 2003;19:353-356.
8. Anera RG, Jimenez JR, Jimenez del Barco L, Bermudez J, Hita E. Changes in corneal asphericity after laser in situ keratomileusis. *J Cataract Refract Surg.* 2003;29:762-768.
9. Chan JW, Edwards MH, Woo GC, Woo VC. Contrast sensitivity after laser in situ keratomileusis. One-year follow-up. *J Cataract Refract Surg.* 2002;28:1774-1779.
10. Boxer Wachler BS. Effect of pupil size on visual function under monocular and binocular conditions in LASIK and non-LASIK patients. *J Cataract Refract Surg.* 2003;29:275-278.
11. Howard IP, Rogers BJ. *Binocular Vision and Stereopsis*. New York, NY: Oxford University Press; 1995.
12. Schor C, Heckmann T. Interocular differences in contrast and spatial frequency: effects on stereopsis and fusion. *Vision Res.* 1989;29:837-847.
13. Pardhan S, Gilchrist J. The effect of monocular defocus on binocular contrast sensitivity. *Ophthalmic Physiol Opt.* 1990;10:33-36.
14. Reading RW. *Binocular Vision: Foundations and Applications*. London, England: Butterworth Publishers; 1983.
15. Legras R, Hornain V, Monot A, Chateau N. Effect of induced anisometropia on binocular through-focus contrast sensitivity. *Optom Vis Sci.* 2001;78:503-509.
16. Jimenez JR, Anera RG, Jimenez R, Salas C. Impact of interocular differences in corneal asphericity on binocular summation. *Am J Ophthalmol.* 2003;135:279-284.
17. Anera RG, Jimenez JR, Jimenez del Barco L, Hita E. Changes in corneal asphericity after laser refractive surgery, including reflection losses and nonnormal incidence upon the anterior cornea. *Opt Lett.* 2003;28:417-419.
18. Holladay JT, Janes JA. Topographic changes in corneal asphericity and effective optical zone after laser in situ keratomileusis. *J Cataract Refract Surg.* 2002;28:942-947.
19. Atchison DA, Smith G. *Optics of the Human Eye*. Oxford, England: Butterworth-Heinemann; 2000.
20. Pardhan S. A comparison of binocular summation in the peripheral visual field in young and older patients. *Curr Eye Res.* 1997;16:252-255.
21. Jimenez JR, Medina JM, Jimenez del Barco L, Diaz JA. Binocular summation of chromatic changes as measured by visual reaction time. *Percept Psychophys.* 2002;64:140-147.
22. Blake R, Fox R. The psychophysical inquiry into binocular summation. *Percept Psychophys.* 1973;14:161-165.
23. Montes-Mico R, Charman WN. Choice of spatial frequency for contrast sensitivity function after corneal refractive surgery. *J Refract Surg.* 2001;17:646-651.
24. Perez-Santonja JJ, Sakla HF, Alio JL. Contrast sensitivity after laser in situ keratomileusis. *J Cataract Refract Surg.* 1998;24:183-189.
25. Mutyala S, McDonald MB, Scheinblum KA, Ostrick MD, Brint SF, Thompson H. Contrast sensitivity evaluation after laser in situ keratomileusis. *Ophthalmology.* 2000;107:1864-1867.
26. Campbell FW, Green DG. Monocular versus binocular visual acuity. *Nature.* 1965;208:191-192.
27. Simmons DR, Kingdom FA. On the binocular summation of chromatic contrast. *Vision Res.* 1998;38:1063-1071.

28. Jimenez JR, Valero E, Anera RG, Martinez JA, Salas C. Chromatic changes in relation to binocular summation determined with contrast thresholds. *Color Research and Application.* 2003;28:366-370.
29. Williams DR, Yoon GY, Guirao A, Hoer H, Porter J. How far can we extend the limits of human vision? In: MacRae SM, Krueger RR, Applegate RA, eds. *Customized Corneal Ablation: The Quest for Super Vision.* Thorofare, NJ: SLACK Inc; 2001:11-34.
30. Krueger RR, Applegate RA, MacRae SM. *Wavefront Customized Visual Correction: The Quest for Super Vision II.* Thorofare, NJ: SLACK Inc; 2004.
31. Quesnel NM, Lovasik JV, Ferremi C, Boileau M, Ieraci C. Laser in situ keratomileusis for myopia and the contrast sensitivity function. *J Cataract Refract Surg.* 2004;30:1209-1218.
32. Pardhan S. A comparison of binocular summation in young and older patients. *Curr Eye Res.* 1996;15:315-319.
33. Lee YC, Hu FR, Wan IJ. Quality of vision after laser in situ keratomileusis: influence of dioptric correction and pupil size on visual function. *J Cataract Refract Surg.* 2003;29:769-777.
34. Helgesen A, Hjortdal J, Ehlers N. Pupil size and night vision disturbances after LASIK for myopia. *Acta Ophthalmol Scand.* 2004;82:454-460.
35. Medina JM, Jimenez JR, Jimenez del Barco L. The effect of pupil size on binocular summation at suprathreshold conditions. *Curr Eye Res.* 2003;26:327-334.
36. Blake R, Levinson E. Spatial properties of binocular neurons in the human visual system. *Exp Brain Res.* 1977;27:221-232.
37. Smallman HS, MacLeod DI. Size-disparity correlation in stereopsis at contrast threshold. *J Opt Soc Am A Opt Image Sci Vis.* 1994;11:2169-2183.
38. Prince SJ, Eagle RA. Stereo correspondence in one-dimensional Gabor stimuli. *Vision Res.* 2000;40:913-924.
39. Jimenez JR, Anera RG, Jimenez del Barco L, Carretero L. Retinal image quality in myopic subjects after refractive surgery. *Journal of Modern Optics.* 2000;47:1587-1598.
40. Jimenez JR, Anera RG, Jimenez del Barco L. Effects on visual function of approximations of the corneal-ablation profile during refractive surgery. *Appl Opt.* 2001;40:2200-2205.
41. Jimenez JR, Anera RG, Jimenez del Barco L. Equation for corneal asphericity after corneal refractive surgery. *J Refract Surg.* 2003;19:65-69.
42. Jimenez JR, Anera RG, Jimenez del Barco L, Hita E. Effect on laser-ablation algorithms of reflection losses and nonnormal incidence on the anterior cornea. *Applied Physics Letters.* 2002;81:1521-1523.
43. Roberts C. Biomechanical customization: the next generation of laser refractive surgery. *J Cataract Refract Surg.* 2005;31:2-5.
44. Anera RG, Villa C, Jimenez JR, Gutierrez R, Jimenez del Barco L. Differences between real and predicted corneal shapes after aspherical corneal ablation. *Appl Opt.* 2005;44:4528-4532.