Wavefront Analysis in Post-LASIK Eyes and Its Correlation with Visual Symptoms, Refraction, and Topography

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Purpose: To evaluate the information assessed with the LADARWave wavefront measurement device and correlate it with visual symptoms, refraction, and corneal topography in previously LASIK-treated eyes.

Participants: One hundred five eyes (58 patients) of individuals who underwent LASIK surgery were evaluated.

Design: Retrospective, noncomparative case series.

Main Outcome Measures: Complete ophthalmologic examination, corneal topography, and wavefront measurements were performed. Correlations were made between the examinations and symptoms.

Methods: Wavefront measurements were assessed with the LADARWave device. Manifest, cycloplegic refraction, and topographic data were compared with wavefront refraction and higher order aberrations. Visual symptoms were correlated to higher order aberrations in 3 different pupil sizes (5-mm, 7-mm, and scotopic pupil size). Pearson's correlation coefficient and generalized estimating equations were used for statistical analysis.

Results: In post-LASIK eyes, wavefront refraction components were poorly correlated to manifest and cycloplegic components. The comparison between manifest, cycloplegic, and wavefront refraction with total amount of higher order aberrations showed no strong correlation. The comparison between topography and manifest, cycloplegic, and wavefront refraction did not show strong correlation. Visual symptoms analysis showed correlation of double vision with total coma and with horizontal coma for the 5-mm and 7-mm pupil size; correlation between starburst and total coma for the 7-mm pupil size; and correlation of double vision with horizontal coma, glare with spherical aberrations and with total aberrations, and starburst with spherical aberrations for the scotopic pupil size. Scotopic pupil size had a positive association with starburst and a negative association with double vision.

Conclusions: The LADARWave wavefront measurement device is a valuable diagnostic tool in measuring refractive error with ocular aberrations in post-LASIK eyes. A strong correlation between visual symptoms and ocular aberrations, such as monocular diplopia with coma and starburst and glare with spherical aberration, suggest this device is valuable in diagnosing symptomatic LASIK-induced aberrations. Horizontal coma was correlated with double vision, whereas vertical coma was not. *Ophthalmology 2004;111:447–453 © 2004 by the American Academy of Ophthalmology.*

Corneal refractive surgeries, such as radial keratotomy, photorefractive keratectomy, and LASIK, are designed to modify the central corneal curvature, making it flatter to correct myopia and steeper to correct hyperopia. This surgical modification might influence the optical quality of the cornea, creating aberrations that will lead to distorted images.[1]

Originally received: December 27, 2002.
Accepted: June 4, 2003. Manuscript no. 220970.

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Maria Regina Chalita, Sai Chavala, and Meng Xu have no financial or proprietary interest in any materials or methods described herein. Ronald R. Krueger receives travel support and research funds from Alcon. Alcon research funds were not expended on this project.

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Although standard laser refractive surgery eliminates conventional refractive errors, higher order aberrations (particularly spherical aberrations) can be induced.[2–4] This might be one of the reasons why patients sometimes complain about the bad quality of vision, even when their visual acuity is 20/25 or 20/20.

Standard refractive surgery takes into consideration only low-order aberrations, which include defocus (myopia and hyperopia) and astigmatism. Wavefront-guided laser refractive surgery considers all the aberrations of the eye, which include the preceding, as well as spherical aberration, coma, and other higher order terms.

The wavefront aberration error is defined as the difference between the actual wavefront (leading edge of propagating rays) and the ideal wavefront in the plane of the eye's exit pupil.[5] Wavefront devices measure monochromatic aberrations,[6] the magnitude of which impacts the acuity and quality of vision.

There are many ways of assessing ocular aberrations,

Published by Elsevier Inc.
ISSN 0161-6420/04/$–see front matter
doi:10.1016/j.ophtha.2003.06.022

including Tscherning aberrometry,[7] Shack–Hartmann wavefront sensing,[8–10] Tracey ray tracing,[11] optical path difference aberrometry,[12] and spatially resolved refractometry.[13] These wavefront devices need to be accurate and reproducible in measuring both refractive error and higher order aberrations when diagnosing complex refractive patients or planning a custom-laser vision correction enhancement.[14]

The LADARWave (Alcon, Fort Worth, TX) device measures spherocylindrical refractive errors (defocus and astigmatism) and higher order aberrations (divided into coma, spherical aberrations, and other terms of high order aberrations). It uses a Shack-Hartmann sensor with an array of lenses that break up the reflected wave of light coming out of the eye into many focused beams. For an ideal eye, the reflected plane wave would be focused into a perfect array of point images, each falling exactly on the optical axis of the corresponding lenslet. By contrast, the aberrated eye focuses the beams of a distorted wavefront into a displaced array of spots, each of which deduces the slope of the aberrated wavefront before it enters the corresponding lenslet. The wavefront can then be analyzed at the level of the eye's exit pupil.

The purpose of this study is to evaluate the information captured with the LADARWave wavefront measurement device in patients previously treated with LASIK for a variety of refractive conditions and to correlate it with clinical findings of refraction, computerized corneal topography, pupil size in scotopic conditions, and visual symptoms in different pupil sizes.

Materials and Methods

One hundred five eyes (58 patients) of individuals who underwent LASIK surgery were enrolled. Eleven patients had surgery just in 1 eye, leaving the other untreated for monovision. The monovision eyes were not evaluated in this study. Thirty-nine were male (67.24%), and 19 were female (32.76%). Mean age was 43.88 years (range, 24–81 years).

All patients in this study were recruited from those having LASIK surgery between 1995 and 2001, both from our service and elsewhere. The patients were arbitrarily selected from all consults done between September 2001 and March 2002. Selection for analysis was not based on whether or not the patient reported visual symptoms.

The patients were submitted to complete ophthalmologic examinations, including manifest refraction in a dark room, cycloplegic refraction, computerized corneal topography (Zeiss-Humphrey, Dublin, CA) before dilatation, and dilated wavefront measurement (LADARWave). One technician performed all wavefront measurements, and written informed consent was obtained from all the subjects for measuring wavefront aberrations. The Institutional Review Board of The Cleveland Clinic Foundation approved this study. Wavefront maps were analyzed using 3 different pupil sizes: 5-mm, 7-mm, and scotopic pupil size.

The refractions (manifest, cycloplegic, and wavefront) were divided into 3 components: sphere, cylinder, and axis. Corneal topography was divided into the magnitude of cylinder and axis. Wavefront sphere was compared with manifest and cycloplegic sphere; wavefront cylinder was compared with manifest, cycloplegic, and topographic cylinder; and wavefront axis was compared with manifest, cycloplegic, and topographic axis. Each of the manifest, cycloplegic, and wavefront parameters were correlated to total aberrations, coma, spherical aberration, and other terms. Coma aberration was subdivided into vertical and horizontal components by use of the sine and cosine formulas, respectively. Mean values for each higher order aberration component were calculated for a 5-mm, 7-mm, and scotopic pupil size.

The match percentage of the wavefront refraction was analyzed. This measurement represents how much of the refractive error acquired by the device is due to just defocus and astigmatism (high percentage) or is influenced by a relatively large amount of higher order aberrations (low percentage). To analyze the influence of match percentage when accessing the wavefront refraction, the sampled values were divided into 2 subgroups: high-matched group and low-matched group. The mean match of all patients in the study was used as a cutoff point.

Optical symptoms (halo, glare, double vision, and starburst) were also asked about individually and separately for each eye. Patients were asked whether they had the symptoms and whether they considered them significant. If so, they were reported on the patient's chart. The patients and the examining physician shared a common nomenclature for optical symptoms. The total number of eyes with each of the symptoms analyzed was halos, 69 eyes; glare, 66 eyes; double vision, 32 eyes; and starburst, 35 eyes. Each symptom was then compared with coma (total, vertical, and horizontal), spherical aberration, other terms of higher order aberrations, and total aberration measurements for a 5-mm, 7-mm, and scotopic pupil size. Scotopic pupil diameter was then correlated to ocular symptoms, independent of the type and magnitude of higher order aberrations.

Statistical Analysis

Pearson's correlation coefficient (0 indicates no linear correlation, ± 1 indicates perfect linear correlation) was assessed for the 2 continuous variables, adjusting for the repeated measurements (refractions), and generalized estimating equations were used to assess the association between symptoms and higher order aberration measurements. Results were considered significant at $P<0.05$.

Results

The mean match percentage was 51%, and this value was used as the cutoff point for 2 subgroups used in our analysis.

The average values of all higher order aberrations for 5-mm, 7-mm, and scotopic pupil size are represented in Figure 1. Scotopic pupil size ranged from 3.0 mm to 8.5 mm, with a mean size of 5.65 ± 1.07 (standard deviation) mm. The larger the pupil size evaluated, the higher the ocular aberration values.

No strong correlations were found when assessing the correlations of manifest refraction and cycloplegic refraction with wavefront refraction, even in the 2 match percentage subgroups (Table 1). Figure 2 shows the scatterplot for manifest sphere versus wavefront sphere of all eyes ($N = 105$).

No strong correlation was found between the pairs when analyzing the correlations of manifest, cycloplegic, and wavefront refraction with total aberration (Table 2).

The comparison between topography and manifest, cycloplegic, and wavefront refraction did not show strong correlation (Table 3).

The association between optical symptoms and higher order aberration for a 5-mm pupil size is represented in Table 4. Double vision was significantly correlated with total coma, as well as horizontal coma ($P = 0.008$ and 0.014, respectively).

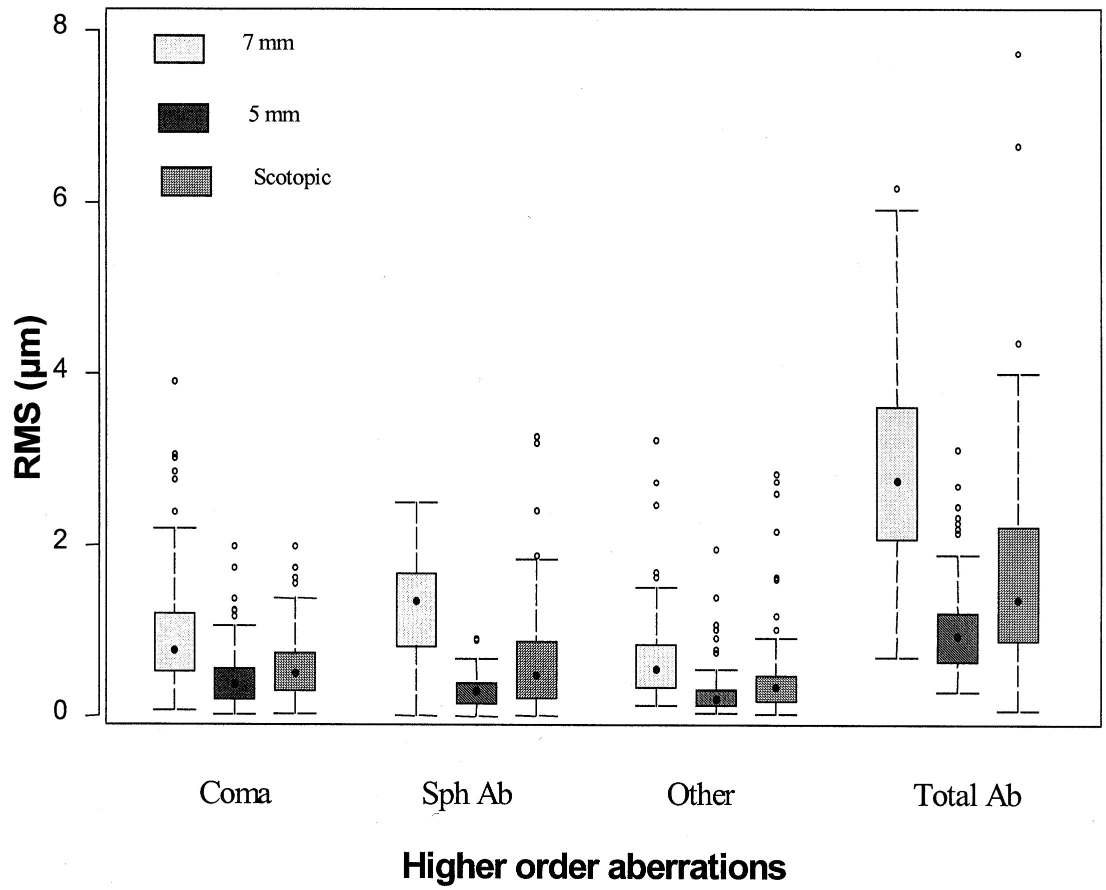

Figure 1. Box plot of root mean square (RMS) error of higher order aberrations for 5-mm, 7-mm, and scotopic pupil sizes. The length of the box represents the interquartile range (the distance between the 25th and the 75th percentiles); the dot in the box interior, the median; the dot outside the box, the outliers; the horizontal lines outside the box, the lower and upper extremes (excluding outliers). Other = other terms of higher order aberrations; sph Ab = spherical aberration; total Ab = total higher order aberrations.

For a 7-mm pupil size, there was a significant correlation of double vision with total coma (P = 0.014) and with horizontal coma (P = 0.024). Starburst was inversely correlated with total coma (P = 0.038) (Table 5).

The analysis of optical symptoms and aberrations for the scotopic pupil size showed statistically significant correlation between glare and spherical aberration (P = 0.010) and glare and total aberration (P = 0.041). Double vision was significantly

Table 1. Correlation Coefficient and 95% Confidence Interval of Manifest Refraction and Cycloplegic Refraction with Wavefront Refraction in Post-LASIK Eyes

	Manifest Sphere	Cycloplegic Sphere	Manifest Cylinder	Cycloplegic Cylinder	Manifest Axis	Cycloplegic Axis
W sph	0.55 (0.40, 0.67)	0.17 (−0.05, 0.37)				
Wcyl			0.28 (0.09, 0.45)	0.40 (0.20, 0.57)		
W axis					0.06 (−0.16, 0.27)	0.37 (0.15,0.55)

	Manifest Sphere Wavefront Sphere	Cycloplegic Sphere Wavefront Sphere	Manifest Cylinder Wavefront Cylinder	Cycloplegic Cylinder Wavefront Cylinder	Manifest Axis Wavefront Axis	Cycloplegic Axis Wavefront Axis
Match 51%	0.88 (0.80, 0.93)	0.04 (−0.27, 0.34)	0.07 (−0.20, 0.33)	0.52 (0.26, 0.71)	0.11 (−0.19, 0.39)	0.52 (0.24, 0.72)
Match <51%	0.08 (−0.21, 0.35)	0.23 (−0.09, 0.51)	0.30 (0.01, 0.54)	0.10 (−0.23, 0.41)	0.44 (0.15, 0.66)	0.23 (−0.12, 0.53)

C = Cycloplegic; cyl = cylinder; M = manifest; sph = sphere; W = wavefront.

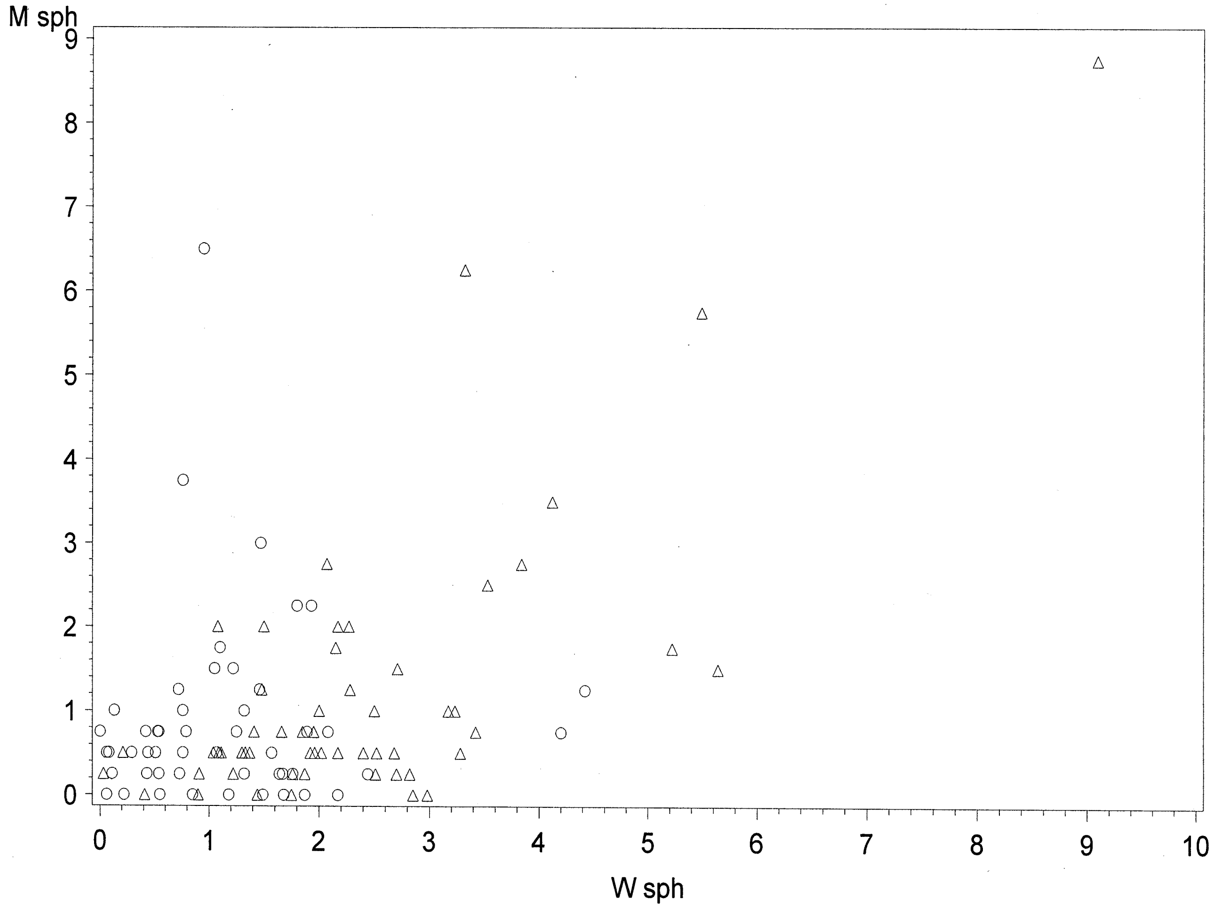

Figure 2. Scatterplot of manifest sphere (M sph) versus wavefront sphere (W sph) (in diopters) for the 2 match subgroups (match≥51%: triangle; match<51%: circle) of post-LASIK eyes. Both shapes together represent the entire sample (105 eyes).

correlated with horizontal coma ($P = 0.033$), and starburst showed statistically significant correlation with spherical aberration ($P = 0.014$) and with total aberration ($P = 0.004$) (Table 6).

The association between scotopic pupil size and optical symptoms showed a negative correlation between pupil diameter and double vision ($P = 0.011$) and a positive correlation between pupil diameter and starburst ($P = 0.001$) (Table 7).

Discussion

Wavefront customized ablation is now the focus of customized corneal ablation to correct ametropias and also to minimize or not induce ocular aberrations. The wavefront analysis gives us a detailed map with defocus, astigmatism, and higher order aberrations.

Different types of wavefront measurement devices can be used to measure defocus, astigmatism, and higher order aberrations, and these devices have been incorporated lately in a clinical setting to help in planning refractive surgeries.[15]

In this study, we evaluated the accuracy of the LADARWave wavefront device compared with clinical data collected from manifest and cycloplegic refraction, computerized corneal topography, pupil size in scotopic conditions,

Table 2. Correlation Coefficient and 95% Confidence Interval of Manifest Refraction, Cycloplegic Refraction, and Wavefront Refraction with Total Aberration in Post-LASIK Eyes

	Manifest Sphere	Cycloplegic Sphere	Wavefront Sphere	Manifest Cylinder	Cycloplegic Cylinder	Wavefront Cylinder	Manifest Axis	Cycloplegic Axis	Wavefront Axis
Total Aber	0.14 (−0.05, 0.32)	0.46 (0.27, 0.62)	0.09 (−0.10, 0.28)	0.29 (0.10, 0.46)	0.41 (0.21, 0.58)	0.45 (0.28, 0.59)	0.13 (0.09, 0.34)	0.013 (−0.22, 0.24)	0.37 (0.19, 0.52)

Total Aber = Total higher order aberrations.

Table 3. Correlation Coefficient and 95% Confidence Interval of Manifest Refraction, Cycloplegic Refraction, and Wavefront Refraction with Topographic Astigmatism Magnitude and Axis in Post-LASIK Eyes

	Manifest Cylinder	Cycloplegic Cylinder	Wavefront Cylinder	Manifest Axis	Cycloplegic Axis	Wavefront Axis
Topographic astigmatism	0.49 (0.33, 0.62)	0.52 (0.34, 0.66)	0.57 (0.42, 0.69)			
Topographic axis				0.16 (−0.06, 0.36)	0.09 (−0.14, 0.31)	0.44 (0.27, 0.58)

and ocular symptoms. We also investigated the role of match percentage in this comparison.

The pupil aperture that is being used for this analysis plays an important role in the results when analyzing the mean values of higher order aberrations. When comparing the 7-mm and the 5-mm measurements, there is a significant difference between them ($P<0.001$), showing that larger apertures have more aberrations in post-LASIK eyes, especially because the peripheral area of the laser treatment is being captured.

In post-LASIK eyes, wavefront refraction was poorly correlated to manifest and cycloplegic refraction. Because the mean match percentage in this post-LASIK group was 51% (much lower than the mean match percentage found by our group when analyzing virgin eyes: 85%), this indicates that only 51% of the refraction given by the wavefront could be attributed to spherical and cylindrical components (lower order aberrations), whereas the remaining 49% would be representative of the higher order aberrations affecting the vision. Even when subdividing the group into subgroups (match percentage ≥51% or <51%), there was no strong correlation between the pairs, and some associations were even smaller when analyzing the lower match subgroup. Lower match percentage means that manifest sphere will represent the best subjective fit to mostly aberrations and therefore will differ from the wavefront sphere. This shows that the more high order aberrations the eye has, the less the wavefront refraction will correlate to manifest and cycloplegic refraction.

No strong correlation was found when comparing the total amount of higher order aberrations with refraction data.

The topographic information did not show any strong correlations with the other clinical data. The 2 coefficients that showed moderate correlation were the wavefront cylinder with topographic cylinder and the wavefront axis with topographic axis. The wavefront information was more highly correlated with topography than with manifest and cycloplegic refractions for all parameters evaluated.

When analyzing higher order aberrations with optical symptoms, double vision was associated with horizontal coma at all pupil sizes analyzed, and total coma was associated with double vision for a 5-mm and 7-mm pupil size. No correlation was found between vertical coma and optical symptoms, showing that not only is the amount of coma important but also its orientation.

Halos revealed a trend of association with spherical aberration for the scotopic pupil size ($P = 0.053$), and glare was significantly associated with spherical aberration and total aberration. These associations were not found for the 5-mm and 7-mm pupil sizes. Starburst also showed significant correlation with spherical aberration and total aberration for the scotopic pupil size. Less intuitively, for the 7-mm pupil size, starburst was inversely associated with total coma.

An interesting observation of our data is the strong correlation of most of the reported visual symptoms with 1 or more of the higher order aberrations when analyzed with the scotopic pupil size. This suggests that the best way of analyzing symptomatic patients is to consider the aberrations of the wavefront map when presented at the diameter of the scotopic pupil, which requires a preoperative knowledge of scotopic pupil size.

A further correlation of pupil diameter under scotopic

Table 4. Odds Ratios and *P* Values of Generalized Estimating Equations Model to Assess Association between Symptoms and Higher Order Aberrations for a 5-mm Pupil Size in Post-LASIK Eyes

		Coma Total	Coma Horizontal	Coma Vertical	Spherical Aberration	Other*	Total Higher Order Aberration
Halos N = 69	Odds ratio	2.8	4.1	1.4	10.7	7.7	2.9
	P	0.37	0.32	0.46	0.18	0.21	0.28
Glare N = 66	Odds ratio	1.5	2.9	0.97	6.4	2.9	1.0
	P	0.69	0.43	0.96	0.41	0.38	0.99
Double vision N = 32	Odds ratio	2.6	7.4	1.2	1.1	1.2	1.6
	P	0.008†	0.014†	0.76	0.90	0.81	0.09
Starburst N = 35	Odds ratio	0.6	1.0	0.6	1.5	1.0	0.91
	P	0.19	0.95	0.42	0.63	0.97	0.78

*Other terms of higher order aberrations.
†Statistically significant.

Table 5. Odds Ratios and *P* Values of Generalized Estimating Equations Model to Assess Association between Symptoms and Higher Order Aberrations for a 7-mm Pupil Size in Post-LASIK Eyes

		Coma Total	Coma Horizontal	Coma Vertical	Spherical Aberration	Other*	Total Aberrations
Halos N = 69	Odds ratio	0.98	1.3	0.9	1.3	1.7	1.2
	P	0.95	0.60	0.57	0.73	0.24	0.68
Glare N = 66	Odds ratio	0.83	0.80	0.8	1.7	1.4	1.1
	P	0.51	0.65	0.40	0.47	0.37	0.69
Double vision N = 32	Odds ratio	1.5	2.7	1.1	1.0	0.8	1.1
	P	0.014†	0.024†	0.72	0.96	0.49	0.47
Starburst N = 35	Odds ratio	0.5	0.7	0.6	0.8	1.1	0.8
	P	0.038†	0.28	0.052	0.76	0.83	0.28

*Other terms of higher order aberrations.
†Statistically significant.

conditions with visual symptoms revealed a significant positive correlation with starburst but a significant negative correlation with double vision. This negative correlation goes against the previous idea that large pupils are correlated to double vision. Rather, one could infer that double vision is correlated with small pupils. This seems less intuitive but is further verified by noting the *P* value of double vision in association with total coma and horizontal coma (Tables 4, 5) are of lower value (more significant) in the 5-mm than 7-mm pupil group. The reason for this negative correlation is unknown but might be related to the fact that double vision because of horizontal coma at a smaller pupil size is more sensitive to the central asymmetry that represents double vision than at a larger pupil size. The peripheral information with a larger pupil negates the perceived central asymmetry and also changes the central coma to another aberration.

The positive correlation of scotopic pupil size with starburst, however, might suggest the importance of planning a larger optical treatment zone for patients with large scotopic pupils. This is because the standard laser ablation with a treatment zone smaller than the scotopic pupil size can induce a high level of spherical aberration. The positive correlation with both scotopic pupil size and starburst warrants additional analysis. It is hoped that customized ablations will minimize this symptom by more effectively correcting the laser-induced spherical aberration.

Our study has some limitations, which will necessitate further studies in the future. These studies may determine the relationship between higher order aberrations and contrast sensitivity, as well as ablation zone size, profile, and depth, to see whether other parameters play an important role in contributing to optical symptoms. Even residual spherical refractive error may be correlated to these symptoms as reported by Kezerian and Stonecipher[16] in uncomplicated LASIK eyes. In this latter study, there is also no correlation of large scotopic pupil size to optical symptoms when a wavefront enhanced ablation profile is used. Another point that could be evaluated and correlated with symptoms is the degree of postoperative keratometric flatness or steepness as recorded by the corneal topographer.

In conclusion, our study demonstrates the usefulness of using the LADARWave wavefront device in measuring post-LASIK ocular aberrations. Strong correlations exist between certain visual symptoms and specific higher order aberrations. These are most frequently noted when analyzing aberrations with a wavefront aperture set at the scotopic pupil size. We recommend symptomatic post-LASIK eyes be evaluated with a wavefront aberrometer, such as the

Table 6. Odds Ratios and *P* Values of Generalized Estimating Equations Model to Assess Association between Symptoms and Higher Order Aberrations for a Scotopic Pupil Size in Post-LASIK Eyes

		Coma Total	Coma Horizontal	Coma Vertical	Spherical Aberration	Other*	Total Aberration
Halos (N = 69)	Odds ratio	1.8	2.9	1.0	3.0	5.2	2.0
	P	0.34	0.20	0.99	0.053	0.13	0.07
Glare (N = 66)	Odds ratio	1.4	2.6	0.90	4.2	6.0	2.20
	P	0.61	0.21	0.80	0.010†	0.10	0.041†
Double Vision (N = 32)	Odds ratio	1.6	3.7	0.80	0.7	0.70	1.0
	P	0.10	0.033†	0.68	0.49	0.40	0.77
Starburst (N = 35)	Odds ratio	0.9	1.5	0.70	6.2	2.30	1.9
	P	0.86	0.24	0.42	0.014†	0.12	0.004†

*Other terms of higher order aberrations.
†Statistically significant.

Table 7. Coefficient and *P* Value to Assess Association between Pupil Diameters in Scotopic Conditions with Symptoms in post-LASIK Eyes

	Halo (N = 69)	Glare (N = 66)	Double Vision (N = 32)	Starburst (N = 35)
Pupil diameter				
Correlation coefficient	0.08	0.46	−1.05	1.52
P	0.78	0.15	0.011*	0.001*

*Statistically significant.

LADARWave, to best determine the nature of the ocular aberrations contributing to their symptoms.

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