Wavefront Aberration Outcomes of LASIK for High Myopia and High Hyperopia

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ABSTRACT

PURPOSE: To determine the higher order aberrations at the corneal first surface after conventional LASIK for high myopia and high hyperopia.

METHODS: This was a retrospective study using a convenience sample with subjects divided into five groups by level of refractive correction. Group 1 were normals, having no eye disease or previous surgery, but may have had refractive error. Group 2 had low myopia (−1.00 to −5.87 D), group 3 high myopia (>6.00 D), group 4 low hyperopia (+1.00 to +3.87 D), and group 5 high hyperopia (>4.00 D). LASIK was performed using a Technolas 217 laser. Corneal topography was taken with Orbscan II, and Placido data exported to VOLPro software v6.71. Wavefront aberrations were determined for a 6.0-mm pupil.

RESULTS: The study included 264 subjects—group 1 (normal), n=204; group 2 (low myopia), n=20; group 3 (high myopia), n=20; group 4 (low hyperopia), n=10; and group 5 (high hyperopia), n=10. The spherical equivalent refractive error corrected (mean±SD) was 0.00±0.00 D in group 1, −3.92±1.47 D in group 2, −9.53±2.06 D in group 3, +2.49±0.51 D in group 4, and +5.54±1.22 D in group 5. The total higher order root-mean-square (RMS) wavefront aberration was 0.38±0.07 μm in group 1, 0.69±0.22 μm in group 2, 1.36±1.79 μm in group 3, 0.64±0.34 μm in group 4, and 1.76±0.54 μm in group 5. Spherical aberration was 0.25±0.06 μm in group 1, 0.45±0.11 μm in group 2, 0.64±0.29 μm in group 3, −0.11±0.15 μm in group 4, and −0.56±0.22 μm in group 5. The refractive correction (Rx) was highly correlated to total higher order RMS for myopic correction higher order RMS=0.38 −0.07Rx, R^2=0.52, and for hyperopic correction higher order RMS=0.18 +0.28Rx, R^2=0.75.

CONCLUSIONS: Conventional LASIK increases all corneal higher order aberrations with induced aberrations increasing with the magnitude of refractive correction. High refractive corrections, both myopic (>6.00 D) and hyperopic (>5.00 D), can lead to very high levels of corneal higher order aberrations. [*J Refract Surg*. 2005;21: S508-S512.]

Conventional laser refractive surgery, whether LASIK or surface ablation, induces an increase in higher order aberrations.[1,2] Most published studies include subjects with low to medium levels of ametropia.[2-5] Studies that have included refractive correction for higher levels of ametropia have included only a few such subjects.[6-11] Although these studies predict higher levels of aberrations for higher corrections, it seems important to document such outcomes. A clinical population in which treatments of high levels of ametropia were performed and well-documented with corneal topography was available for study. Therefore, the purpose of this study was to determine the higher order aberrations at the corneal first surface after conventional LASIK for high myopia and high hyperopia. Although the measurement of whole eye aberrations may seem to be a preferable outcome measure to corneal aberrations, measured aberrations induced at the cornea and in the whole eye after LASIK have previously been shown to be highly correlated (r=0.97).[6] Certainly, as induced corneal aberrations increase, they approach whole eye aberrations, and because the cornea is the location of the refractive correction, corneal aberrations represent a convenient and well-established model for performing this study.

PATIENTS AND METHODS

This was a retrospective study using a convenience sample with subjects divided into five groups by level of refractive correction. Group 1 were normals, having no eye disease or previous surgery, but may have had refractive error. Group 2 had low myopia (−1.00 to −5.87 diopters [D]), group 3 high myopia (>6.00 D), group 4 low hyperopia (+1.00 to +3.87 D), and group 5 high hyperopia (>4.00 D).

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TABLE 1

Study Population

	Group				
	Normal	Low Myopia	High Myopia	Low Hyperopia	High Hyperopia
Refractive error eligibility (D)	NA	−1.00 to −5.87	>6.00	+1.00 to +3.87	>+4.00
No. eyes	204	20	20	10	10
Refractive error corrected (D)	NA	−3.92±1.47	−9.53±2.06	+2.49±0.51	+5.54±1.22
Mean time to follow-up (mo)	NA	6.5±4.8	6.9±5.7	8.1±5.2	11.3±8.0

Laser in situ keratomileusis was performed, by a number of different surgeons, under topical anesthesia using the Technolas 217 (V2 9997) excimer laser and the Hansatome microkeratome (Bausch & Lomb, Rochester, NY). In all eyes, a 160-µm head was used, and where possible, the 9.5-mm diameter ring, otherwise the 8.5-mm diameter ring was used. The optical zone was at least 6.0 mm, being increased to 0.5 mm greater than the scotopic pupil for pupils >5.5 mm. All surgeries were bilateral and performed between 1999 and 2001 at Ultralase, Leeds, United Kingdom. All patients consented to the use of their data and the study was approved by the Leeds Regional Ethics Committee.

All data were drawn from clinical records. Corneal topography was taken with Orbscan II (Bausch & Lomb, Rochester, NY), and Placido ring data recorded to text files. These data were imported into VOLPro software v6.71 (Sarver & Associates, Fla) for the calculation of wavefront aberrations. A 10th order Zernike expansion was used. A 6.0-mm pupil was chosen for ease of comparison with existing studies, and pupil center was assumed to be at the corneal vertex.

Data were stored in a spreadsheet and descriptive statistics (mean and standard deviation [SD]) were calculated. The relationship between refractive error treated and each Zernike mode and order was determined using linear regression (five randomly selected normal eyes were included in the post-LASIK groups to extend the treated range to zero diopters). All statistical analyses were performed on Statistical Package for the Social Sciences for windows v11.1 (SPSS Inc, Chicago, Ill).

RESULTS

The total population comprised 264 subjects. The number in each group and the refractive error treated are listed in Table 1. The mean time to follow-up was 7.7 months (SD 5.8 months), which was not significantly different across groups: $F_{3,57}=1.42$, $P>.05$. The pattern of wavefront aberrations varied across groups. This is illustrated in Figure 1 by Zernike order and Figure 2 by Zernike mode. Large increases in total higher order root-mean-square (RMS) were primarily mediated by 3rd and 4th orders, although for the higher corrections, both myopic and hyperopic, 5th to 10th orders were also elevated beyond normal (see Fig 1). In all groups, coma, trefoil, and spherical aberration (opposite in sign for hyperopic treatments) dominated the wavefront error with higher frequency orders becoming elevated with increasing refractive error corrected (see Fig 2). By diopters corrected, hyperopic LASIK induces five to six times more aberrations than myopic LASIK (see Fig 1).

The refractive correction, expressed as spherical equivalent (SphEq), was correlated to the post-surgical wavefront aberrations (Table 2). The relationships were particularly strong for 3rd and 4th order aberrations, especially spherical aberration and coma, but also for the very high orders and the total higher order RMS (Fig 3). These relationships varied for myopic and hyperopic corrections, generally being stronger for hyperopic treatments. Strong correlations were noted between refractive error and all order of wavefront aberrations for hyperopic ablation (R^2=0.40 to 0.76), whereas in the myopic treatments spherical aberration dominated the relationship with refractive correction (R^2=0.61).

DISCUSSION

The levels of total higher order RMS after conventional LASIK refractive surgery are similar to previous reports for low myopic,[2,6,7] high myopic,[9,10] low hyperopic,[3,4] and high hyperopic subjects.[8,11] The increases in total higher order RMS are dominated by 3rd and 4th order wavefront errors, and similar data after conventional LASIK for myopia[7] and hyperopia[4] have been reported. However, the increases in wavefront error in orders 5 to 10 for high myopic and high hyperopic corrections have not previously been reported. Similarly, few studies report outcomes of individual modes, and

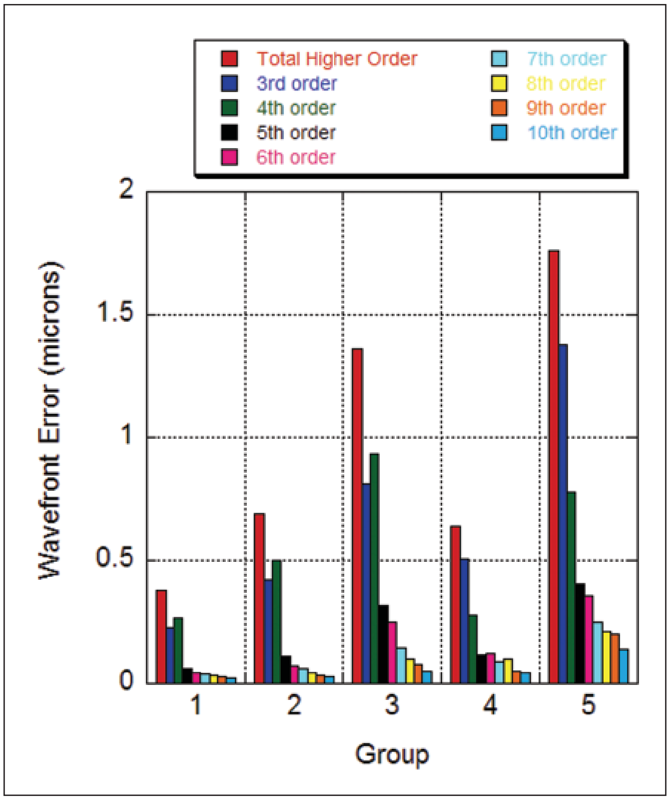

Figure 1. Higher order aberrations—total and 3rd through 10th orders for each group: group 1 normal, group 2 low myopia, group 3 high myopia, group 4 low hyperopia, and group 5 high hyperopia.

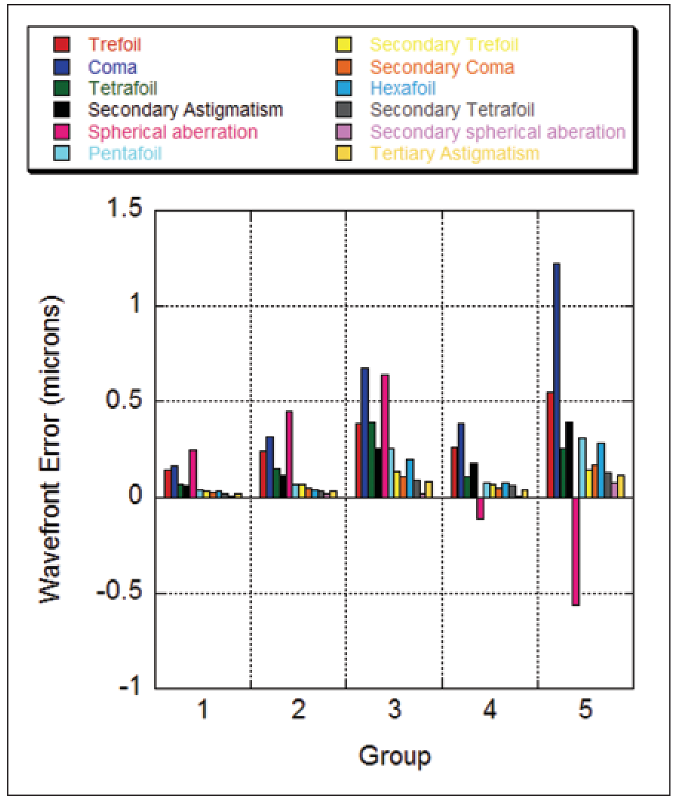

Figure 2. Higher order aberrations by paired Zernike modes from 3rd through 6th orders for group 1 normal, group 2 low myopia, group 3 high myopia, group 4 low hyperopia, and group 5 high hyperopia.

those are mostly confined to coma and spherical aberration.[2,6-9] The positive spherical aberration induced by myopic ablation and the negative spherical aberration induced by hyperopic LASIK is consistent with previous studies.[3,4] The increases in high frequency modes with high treatments, especially for hyperopia, is a novel finding and is likely caused by the hyperopic ablation profile being deeper peripherally; however, it is unclear whether these aberrations arise during treatment or healing. Hyperopic LASIK tends to induce more aberrations (five to six times more) than myopic LASIK for the same level of refractive error corrected.[4]

The relationship between refractive correction (spherical equivalent) and total higher order RMS for myopia and hyperopia is similar to previous reports.[6,8] Similarly, the relationship between refractive correction and spherical aberration, for myopia and hyperopia, is comparable with previous reports.[3,4,7] However, the relationships between most of these Zernike orders and Zernike modes and refractive correction have not been previously reported. The regression equations reported herein may be valuable for predicting visual outcomes, or determining acceptable limits of surgical refractive correction. These equations would have greater validity if generated from a larger population; nevertheless this is the largest series of patients undergoing LASIK for high ametropia where wavefront aberrations have been reported. Interestingly, the predictability of wavefront aberration outcomes seems better after hyperopic LASIK than myopic LASIK. This may be due to the higher amounts of aberrations induced by hyperopic LASIK.

These data add to the literature on the aberrations induced by conventional LASIK. Most studies reporting aberrations after refractive surgery have only included a few, if any, cases of high treatments. These high levels of induced aberrations after LASIK refractive surgery emphasize the role of ablation design to prevent the induction of these aberrations. This is important because wavefront aberrations induced in LASIK refractive surgery correlate with symptoms of visual problems.[12] More recent reports of wavefront-guided LASIK outcomes have reported lower levels of induced total higher order RMS and spherical aberration.[13-15]

Coma was a major aberration for hyperopic LASIK subjects. However, this must be interpreted with some caution as the reference axis will affect this result. Ideally, the line of sight should be used,[16] but this was not available and therefore not accounted for in

TABLE 2

Linear Regression Equations for Zernike Pairs and Orders by Spherical Equivalent Refractive Error (SphEq)

Aberration	Myopia Equation (SphEq)	R^2 %	Hyperopia Equation (SphEq)	R^2 %
Total Higher Order	=0.38 −0.07	52	=0.18 +0.28	75
Orders				
3rd	=0.25 −0.04	33	=0.05 +0.24	76
4th	=0.27 −0.05	59	=0.18 +0.10	65
5th	=0.06 −0.01	17	=0.03 +0.06	42
6th	=0.03 −0.01	20	=0.04 +0.05	40
7th	=0.03 −0.01	9	=0.02 +0.04	44
8th	=0.02 −0.01	15	=0.03 +0.04	40
9th	=0.02 −0.00	19	=−0.01 +0.04	58
10th	=0.02 −0.00	30	=0.00 +0.03	61
Individual Aberrations				
Trefoil	=0.18 −0.00	2	=0.14 +0.06	42
Coma	=0.16 −0.04	29	=−0.05 +0.24	72
Tetrafoil	=0.09 −0.01	19	=0.06 +0.04	28
Secondary astigmatism	=0.07 −0.01	15	=0.06 +0.06	52
Spherical aberration	=0.24 −0.05	61	=0.25 −0.15	83
Pentafoil	=0.02 −0.01	20	=0.00 +0.05	37
Secondary trefoil	=0.05 −0.00	3	=0.04 +0.02	13
Secondary coma	=0.03 −0.00	17	=0.01 +0.02	41
Hexafoil	=−0.01 −0.01	15	=0.02 +0.04	40
Secondary tetrafoil	=0.02 −0.00	12	=0.02 +0.02	20
Tertiary astigmatism	=0.02 −0.00	32	=0.02 +0.02	29
Secondary spherical aberration	=0.01 −0.00	2	=−0.01 +0.01	20

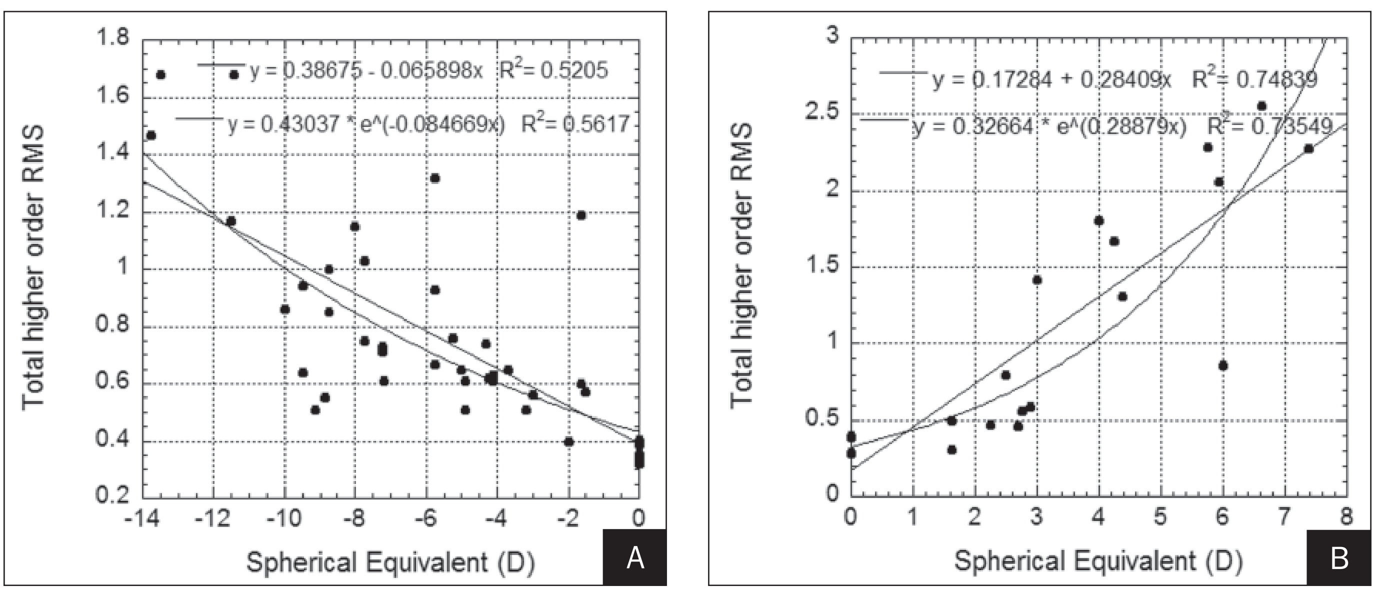

Figure 3. Scatterplot of refractive error, as spherical equivalent (D), against total higher order RMS (μm) for **A)** myopia and **B)** hyperopia giving the linear regression and exponential curve fits.

the experimental design. A previous study looking at low hyperopic ablation only did not find coma to be as prominant.[3] However, our results demonstrate that coma is particularly prominent with high hyperopic ablation.

Optical quality metrics other than RMS may yield more information about the visual impact of these aberrations.[17,18] Although RMS has been suggested to be limited in its correlation with visual performance, this is true mainly at low levels.[19] At the higher levels of RMS seen in this study, RMS is a good indicator of visual performance.[20]

Conventional LASIK increases all corneal higher order aberrations, in comparison with normal (non-treated) control eyes, with induced aberrations increasing with the strength of refractive correction. High refractive corrections, both myopic (−6.00 D) and hyperopic (+4.00 D), can lead to high levels of corneal higher order aberrations.

REFERENCES

1. 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.
2. 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.
3. Wang L, Koch DD. Anterior corneal optical aberrations induced by laser in situ keratomileusis for hyperopia. *J Cataract Refract Surg.* 2003;29:1702-1708.
4. Llorente L, Barbero S, Merayo J, Marcos S. Total and corneal optical aberrations induced by laser in situ keratomileusis for hyperopia. *J Refract Surg.* 2004;20:203-216.
5. Porter J, MacRae S, Yoon G, Roberts C, Cox IG, Williams DR. Separate effects of the microkeratome incision and laser ablation on the eye's wave aberration. *Am J Ophthalmol.* 2003;136:327-337.
6. Marcos S, Barbero S, Llorente L, Merayo-Lloves J. Optical response to LASIK surgery for myopia from total and corneal aberration measurements. *Invest Ophthalmol Vis Sci.* 2001;42:3349-3356.
7. 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.
8. Ma L, Atchison DA, Albietz JM, Lenton LM, McLennan SG. Wavefront aberrations following laser in situ keratomileusis and refractive lens exchange for hypermetropia. *J Refract Surg.* 2004;20:307-316.
9. Hersh PS, Fry K, Blaker JW. Spherical aberration after laser in situ keratomileusis and photorefractive keratectomy. Clinical results and theoretical models of etiology. *J Cataract Refract Surg.* 2003;29:2096-2104.
10. Buzzonetti L, Iarossi G, Valente P, Volpi M, Petrocelli G, Scullica L. Comparison of wavefront aberration changes in the anterior corneal surface after laser-assisted subepithelial keratectomy and laser in situ keratomileusis: preliminary study. *J Cataract Refract Surg.* 2004;30:1929-1933.
11. Oliver KM, O'Brart DP, Stephenson CG, Hemenger RP, Applegate RA, Tomlinson A, Marshall J. Anterior corneal optical aberrations induced by photorefractive keratectomy for hyperopia. *J Refract Surg.* 2001;17:406-413.
12. Chalita MR, Chavala S, Xu M, Krueger RR. Wavefront analysis in post-LASIK eyes and its correlation with visual symptoms, refraction, and topography. *Ophthalmology.* 2004;111:447-453.
13. Awwad ST, El-Kateb M, Bowman RW, Cavanagh HD, McCulley JP. Wavefront-guided laser in situ keratomileusis with the Alcon CustomCornea and the VISX CustomVue: three-month results. *J Refract Surg.* 2004;20:S606-S613.
14. Slade S. Contralateral comparison of Alcon CustomCornea and VISX CustomVue wavefront-guided laser in situ keratomileusis: one-month results. *J Refract Surg.* 2004;20:S601-S605.
15. Kim TI, Yang SJ, Tchah H. Bilateral comparison of wavefront-guided versus conventional laser in situ keratomileusis with Bausch and Lomb Zyoptix. *J Refract Surg.* 2004;20:432-438.
16. Applegate RA, Thibos LN, Bradley A, Marcos S, Roorda A, Salmon TO, Atchison DA. Reference axis selection: subcommittee report of the OSA Working Group to establish standards for measurement and reporting of optical aberrations of the eye. *J Refract Surg.* 2000;16:S656-S658.
17. Marsack JD, Thibos LN, Applegate RA. Metrics of optical quality derived from wave aberrations predict visual performance. *J Vis.* 2004;4:322-328.
18. Pesudovs K. Single-value metrics of wavefront aberration—are we there yet? *J Refract Surg.* 2004;20:S493-S494.
19. Applegate RA, Ballentine C, Gross H, Sarver EJ, Sarver CA. Visual acuity as a function of Zernike mode and level of root mean square error. *Optom Vis Sci.* 2003;80:97-105.
20. Smolek MK, Klyce SD. Zernike polynomial fitting fails to represent all visually significant corneal aberrations. *Invest Ophthalmol Vis Sci.* 2003;44:4676-4681.