Optical Profile Following High Hyperopia Correction With a 500-Hz Excimer Laser System

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ABSTRACT

PURPOSE: To evaluate corneal higher order aberrations after LASIK for the correction of high hyperopia using a 500-Hz excimer laser and optimized ablation profile.

METHODS: Retrospective consecutive study including 51 eyes of 28 patients (age range: 21 to 54 years) with high hyperopia or hyperopic astigmatism (sphere ≥ 5.00 diopters). All cases underwent LASIK using the sixth generation Amaris excimer laser (SCHWIND eye-tech-solutions, Kleinostheim, Germany) and a femtosecond laser platform for flap creation. Postoperative changes in corneal higher order aberrations for the 4-, 5-, and 6-mm pupil diameters and corneal asphericity for 4.5 and 8 mm were represented at the end of the 6-month follow-up.

RESULTS: A significant increase in corneal root mean square higher order, spherical, and coma aberrations was observed 6 months after surgery ($P < .01$). Corneal asphericity for the 4.5-mm (Q45) and 8-mm (Q8) corneal diameter also changed significantly during the postoperative period ($P < .01$). Strehl ratio change was not statistically significant ($P = .77$).

CONCLUSIONS: Correction of high hyperopia with LASIK significantly induces corneal higher order aberrations regardless of the physiologic level of photopic and mesopic pupil conditions.

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The correction of hyperopia with excimer laser has been a challenge for corneal refractive surgeons. The main problem has been the creation of a curved surface that should have an adequate centration and useful optical zone to allow good quality of vision. Issues related to the lack of orthogonality of the excimer laser beam onto the cornea, centration of the procedure, the transition between the optical zone and the non-ablated cornea, and the time and energy that this procedure requires, which induces corneal epithelial and stromal biological reactions typical of wound healing, have all influenced the outcomes.[1-4]

Currently, no consensus on the limits of hyperopic LASIK has been established. Some authors define the limit as +5.00 to +7.00 diopters (D), whereas others recommend hyperopic LASIK for only low to moderate hyperopia up to +3.00 to +4.00 D.[5,6]

The aim of this study was to evaluate the corneal optical quality after high hyperopic correction with LASIK using a 500-Hz excimer laser with an optimized ablation profile.

PATIENTS AND METHODS

PATIENTS

This was a retrospective, consecutive non-comparative study of 51 eyes of 28 patients with ages ranging from 21

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to 54 years (mean age: 33 ± 9 years) that underwent uneventful primary LASIK surgery. Inclusion criteria were eyes with high hyperopia (sphere +5.00 D or greater) discontinuing the contact lens wear for at least 4 weeks before surgery, stable refractive error for 12 months before surgery, normal peripheral retina, a calculated postoperative corneal residual stromal bed thickness of more than 250 µm at the thinnest corneal area following the surgery, and no previous ocular surgery, corneal disease, glaucoma, or history of ocular trauma. Exclusion criteria were keratoconus or keratectasia, active ocular or systemic disease that could affect corneal wound healing, and pregnancy. Patients with amblyopia and a potential distance visual acuity of worse than 20/40 (0.3 logMAR) were also excluded. Before surgery each patient was adequately informed about the surgery, its risks, and its benefits. Approval from the ethical board committee of our institution was obtained for this investigation.

Preoperative Examination

The preoperative examination included the following tests: uncorrected distance visual acuity (UDVA), corrected distance visual acuity (CDVA), refraction (manifest and cycloplegic), slit-lamp biomicroscopy, applanation tonometry, ultrasonic pachymetry (OcuScan RxP; Alcon Laboratories, Inc., Fort Worth, TX), scotopic, low, and high mesopic pupillometry (Procyon Pupillometer P2000SA; Procyon Instruments Ltd., London, UK), corneal topography (Eyetop; CSO, Firenze, Italy), and fundus evaluation. Corneal aberrations were derived from the data of the anterior surface of the cornea obtained with the CSO topography system. The software of this topography system, the Eyetop2005, converts the corneal topographic data into corneal wavefront data using the Zernike polynomials with an expansion up to the seventh order. Aberration coefficients and root mean square (RMS) values were obtained for 4-, 5-, and 6-mm pupil diameters simulating different light conditions. The RMS values were computed for total aberrations, higher order aberrations (coefficients from third to seventh order), coma-like aberrations $Z^3_{\pm1}$ and $Z^5_{\pm1}$, and spherical-like aberrations Z^4_0 and Z^6_0. The corresponding Zernike coefficient for primary spherical aberration, Z^4_0, was reported with its sign and the primary coma RMS (computed for the Zernike terms $Z^3_{\pm1}$). The asphericity was calculated from corneal topography at 4.5 and 8 mm with the consideration of coupling effects of conic fits.[7] The CSO software automatically provided the corneal Strehl ratio, which is a single value representing the point spread function. This ratio is defined as the ratio of peak focal intensities in the aberrated to ideal point spread function.

The CSO Eyetop uses the corneal vertex as the central reference. When calculating the corneal aberrations (corneal wavefront in the SCHWIND terminology), the surface aberration (which is calculated as the difference considering a regular cornea in the shape of a Cartesian oval [Q = -1 / n^2 = -0.528] with no astigmatism and centered on the corneal vertex) is converted into optical path difference (or waavefront error) and the Zernike fit is referred to the pupil center (to make it conform to Optical Society of America, International Standards Organization, and American National Standards Institute standards, but also to allow better comparability to whole eye wavefront and in line with Applegate et al.'s findings[8]).

Excimer Laser and Ablation Profile

LASIK was performed using the Amaris excimer laser (SCHWIND eye-tech-solutions, Kleinostheim, Germany). This system has a repetition rate of 500 Hz and incorporates two levels of fluence.[9] A small beam size of 0.54 mm with a Gaussian ablative spot profile is delivered in a randomized flying spot pattern to reduce the successive overlapping of the laser spot and minimize the thermal load to the cornea.[10] This laser platform has incorporated a five-dimension high-speed eye tracker with an acquisition speed of 1,050 Hz that tracks both the limbus and the pupil simultaneously with a reaction time of less than 3 ms.[8] All treatments performed were based on optimized aspherical ablation profiles and calculated using the commercially available software ORK-CAM (version 4.1.4112.450) from SCHWIND eye-tech-solutions. This optimized aspherical aberration-free profile considers a focus-shift balance due to tissue removal and a compensation factor for the loss of efficiency because the laser beam does not affect the periphery of the ablation zone perpendicular to the surface of the cornea, a phenomenon that is often referred as the "cosine effect," to avoid the induction of aberrations and to balance the aberrations that are present in the treated eye.[11]

Surgical Technique

All surgical procedures were performed at Vissum Alicante by an experienced surgeon (JLA). First, the designed treatment with the ORK-CAM software was loaded into the excimer laser computer and reviewed by the surgeon to confirm the data. The corneal flap was created with the IntraLase femtosecond laser (60-kHz IntraLase femtosecond system; IntraLase Corp., Irvine, CA) using the following parameters: temporal hinge, 9.5-mm diameter, line and spot spacing of 7 µm pocket function on status "ON," and flap thickness of 100 µm.

Ablations were centered on the pupil center. The optical zone of the treatment was selected according to the preoperative scotopic pupil size. Depending on the pachymetry, optical zones with at least the same diameter as the scotopic pupil were targeted to avoid uncomfortable optical effects.

The optical zone of the ablation area ranged between 6.2 and 6.9 mm, with most of the cases having a 6.5-mm optical zone with a transition zone of 2.5 mm. The optical zone was decided according to the largest zone possible to ablate the stroma, leaving a residual stromal bed greater than 250 µm and not removing more than 40% of stromal thickness at any level of the ablation area.

Re-treatments

The criteria for re-treatment included one of the following parameters: (1) manifest spherical equivalent of ±1.00 D or greater, (2) UDVA of 0.3 logMAR or worse, and (3) patient dissatisfaction with the visual result. Undercorrection was defined as a spherical equivalent of +1.00 D or greater at the first postoperative visit. Regression was noted when a 0.50 D or greater hyperopic shift occurred between follow-up visits without re-treatment. All enhancements were performed at least 3 months after the initial surgery.

Postoperative Follow-up

Patients were examined on the first postoperative day and at 1, 3, and 6 months after surgery. On the first postoperative day, a detailed slit-lamp examination was performed to evaluate the flap position and the integrity of the cornea. At the rest of the postoperative visits, UDVA, manifest and cycloplegic refraction, CDVA, anterior segment status (slit-lamp biomicroscopy), corneal topography, and aberrometry were evaluated. An independent observer performed all of the postoperative examinations.

Statistical Analysis

Statistical analysis was performed with the SPSS statistical software package version 10.1 for Windows (SPSS, Inc., Chicago, IL). Normality of the data analyzed was confirmed by the Kolmogorov–Smirnov test. When parametric analysis could be applied, the Student's *t* test for paired data was used for the comparison between preoperative and postoperative data, and also between postoperative consecutive visits. However, when non-parametric tests were needed, the Wilcoxon rank sum test was applied. Differences were considered statistically significant when the associated *P* value was less than .05. Correlation coefficients (Pearson or Spearman depending on whether normality condition could be assumed) were used to assess the correlation between different variables.

Main outcomes measured were corneal aberrations, corneal asphericity, and corneal optical quality.

RESULTS

Fifty-one eyes were evaluated at 3 months, 27 eyes (52.9%) were evaluated at 6 months, and 9 eyes (17.6%) were lost to follow-up. Fifteen eyes (29.4%) were re-treated. Postoperative visits after the re-treatment were excluded from the refractive analysis to avoid biased results. **Table 1** summarizes the visual, refractive, and corneal optical quality for 6-mm pupil diameter outcomes obtained in this study. **Table A** (available in the online version of this article) summarizes the corneal optical quality outcomes for the 5-mm pupil diameter, whereas **Table B** (available in the online version of this article) reports aberrations for the 4-mm pupil diameter.

A large and statistically significant reduction of the spherical equivalent was observed at 6 months after surgery. We also found that 70.8% of the cases were within ±1.00 D of intended correction 6 months after the surgery. UDVA improved significantly at 3 months postoperatively, with an average improvement of 4.2 lines. No significant changes in this parameter were observed after this time. A total of 86% of the eyes presented a UDVA of 20/40 (0.2 logMAR) or better at 6 months after surgery (**Figure 1A**), whereas 17.5% of eyes lost one or more lines of CDVA after surgery (**Figure 1B**).

Corneal Asphericity and Corneal Aberrations

Corneal asphericity for both 4.5- and 8-mm diameter pupils decreased significantly. The RMS HOA showed a statistically significant increase (**Figures 2-3**). **Figure 4** shows a histogram graph of cumulative eyes depending on the corneal RMS HOA range. A reduction was seen when we analyzed the RMS astigmatism at 6 months.

Figure 5 shows a histogram graph of cumulative eyes depending on the corneal Strehl ratio range.

Correlations and Multiple Linear Regression Analysis Models

The aim of this study was to correlate the preoperative and postoperative variables.

The RMS spherical-like aberrations are affected positively by the preoperative sphere and negatively by the preoperative steepest meridian of the cornea (K2): $RMS\_SPHLK_{3m} = 1.895 + 0.105 \times Sphere_{PRE} - 0.045 \times K2_{PRE}$.

Each diopter of preoperative sphere to be corrected induces approximately 0.1 µm of RMS spherical-like aberrations at 3 months, but each diopter of K2 reduces 0.045 µm of RMS spherical-like aberrations at 3 months. Therefore, axial hyperopic eyes (small axial length and large K2) will present fewer RMS spherical-

TABLE 1

Anterior Corneal Aberrations for 6-mm Pupil Diameter[a]

Parameter	Preoperative	3 Months Postoperative	6 Months Postoperative	P^b
Sphere (D)	+6.33 ± 0.83 (+5.00 to +8.50)	+0.48 ± 0.85 (-0.75 to 2.75)	+0.67 ± 1.21 (-0.50 to 4.00)	< .01
Spherical equivalent (D)	+5.64 ± 0.93 (3.50 to 7.88)	-0.14 ± 0.80 (-1.13 to 2.50)	+0.50 ± 1.06 (-0.50 to 3.38)	< .01
Cylinder	-1.39 ± 0.96 (-3.75 to 0.0)	-0,71 ± 0,53 (-2.25 to 0.0)	-0.32 ± 0.60 (-2.0 to 0.0)	< .01
UDVA (logMAR)	0.52 ± 0.31 (0 to 1.3)	0.10 ± 0.12 (0 to 0.44)	0.08 ± 0.12 (0 to 0.44)	< .01
CDVA (logMAR)	0.02 ± 0.09 (0.07 to 0.44)	0.04 ± 0.08 (0 to 0.36)	0.03 ± 0.07 (-0.03 to 0.30)	.975
RMS Total (μm)	1.74 ± 0.65 (0.83 to 3.17)	2.76 ± 1.07 (1.09 to 5.82)	2.28 ± 0.79 (1.36 to 4.86)	.037
Zernike coefficient (Z^4_0) (μm)	0.18 ± 0.16 (-0.36 to 0.59)	-0.47 ± 0.23 (-1.05 to 0.02)	-0.55 ± 0.25 (-2.32 to 0.79)	< .01
Zernike coefficient (Z^3_{+1}) (μm)	0.65 ± 0.54 (-1.90 to 1.64)	0.23 ± 0.57 (-1.36 to 1.07)	0.20 ± 0.52 (-1.25 to 1.23)	.10
Zernike coefficient (Z^3_{-1}) (μm)	0.03 ± 0.21 (-0.61 to 0.35)	-0.24 ± 0.47 (-1.26 to 0.95)	-0.66 ± 0.36 (-1.21 to 0.03)	< .01
RMS AST (μm)	1.36 ± 0.74 (0.19 to 2.97)	1.41 ± 0.64 (0.25 to 2.65)	1.17 ± 0.45 (0.36 to 1.92)	.224
RMS residual (μm)	0.26 ± 0.11 (0.11 to 0.63)	0.50 ± 0.16 (0.24 to 0.85)	0.49 ± 0.18 (0.26 to 0.68)	< .01
RMS spherical-like (μm)	0.27 ±0.08 (0.14 to 0.55)	0.57 ± 0.22 (0.25 to 1.08)	0.64 ± 0.25 (0.19 to 1.17)	< .01
RMS coma-like (μm)	0.44 ± 0.14 (0.19 to 0.85)	0.86 ± 0.36 (0.33 to 1.92)	0.74 ± 0.11 (0.19 to 1.61)	.005
RMS HOA (μm)	0.52 ± 0.14 (0.31 to 0.89)	1.06 ± 0.35 (0.47 to 2.13)	0.91± 0.40 (0.00 to 1.61)	.002
Strehl ratio	0.08 ± 0.04 (0.03 to 0.19)	0.09 ± 0.30 (0.05 to 0.15)	0.08 ± 0.02 (0.05 to 0.15)	.777

D = diopters; UDVA = uncorrected distance visual acuity; CDVA = corrected distance visual acuity; RMS = root mean square; AST = astigmatism; HOA = higher order aberrations

[a]Values are given as mean ± standard deviation (range). All aberrations are anterior.

[b]Preoperative to 3 months.

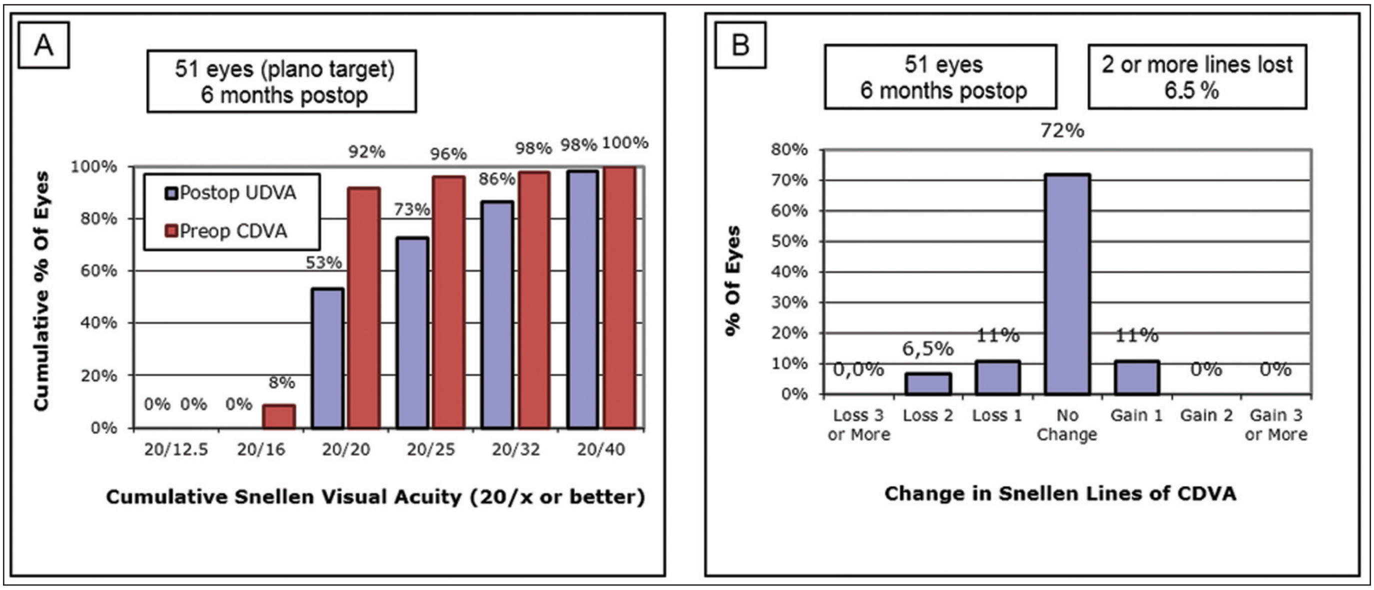

Figure 1. (A) Standard graph of cumulative distribution of uncorrected distance visual acuity. (B) Standard graph of lines change of corrected distance visual acuity. UDVA = uncorrected distance visual acuity; CDVA = corrected distance visual acuity

like aberrations than hyperopic eyes with a flat cornea (large axial length and small K2).

We also found a linear regression model for the cylinder at 3 months because it is negatively affected by the preoperative cylinder and the preoperative spherical and spherical-like aberrations: $\text{Cylinder}_{3m} = -0.138 + 0.275 \times \text{Cylinder}_{PRE} - 7.000 \times \text{RMS\_SA}_{PRE} - 6.734 \times \text{RMS\_SPHLK}_{PRE}$.

Each 0.1 μm of preoperative RMS_SA affects the postoperative cylinder by 0.70 D and each 0.1 μm of preoperative RMS spherical-like aberrations affects the postoperative cylinder by 0.67 D.

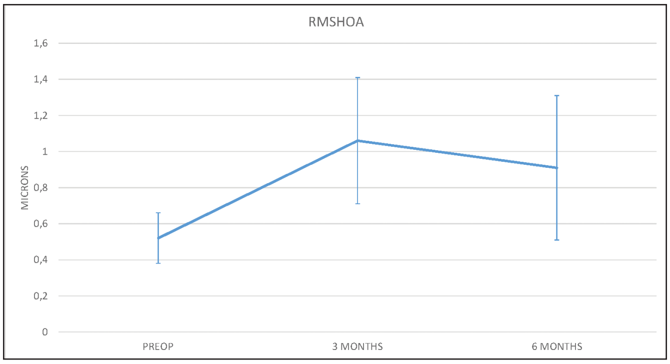

Figure 2. Corneal root mean square higher order aberrations (RMS HOA) ± standard deviation.

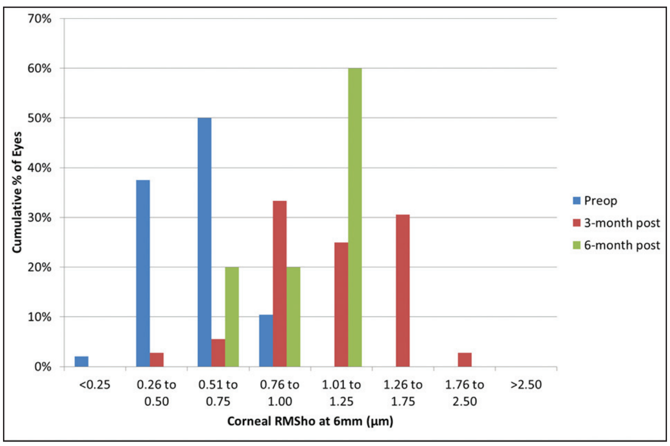

Figure 4. Histogram of preoperative and postoperative root mean square higher order aberrations (RMS HOA).

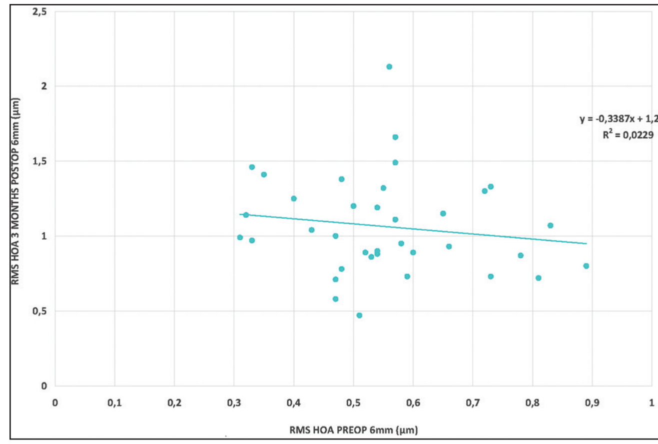

Figure 3. Preoperative and postoperative corneal root mean square higher order aberrations (RMS HOA).

Figure 6 shows the linear regression model between the hyperopia treated and the difference between preoperative and postoperative RMS HOA for a 6-mm pupil. For each diopter of sphere treated, 0.17 µm of RMS HOA was induced: Change HOA = 0.08 × Sphere +0.09

DISCUSSION

In our study, the RMS HOA increased by a factor of 1.75 (postoperative/preoperative). Although some investigators[4,12] reported less induction of HOAs with the SCHWIND Esiris Laser Platform using an ablation optical zone of 6 mm[4] and an optical zone of 6.5 mm,[11] others[13] compared the corneal aberrations of two excimer platforms (VISX Star S2 and the Asclepion-Meditec MEL 70 G Scan) using the same optical zone of 6 mm. They investigated two samples of moderate hyperopia with mean preoperative spherical equivalent of +2.83 and +2.90 D with an optical zone ablation diameter of 6 mm in both groups. They encountered an induction of HOAs when they studied the 6.5-mm aperture diameter of anterior surface of cornea of a factor of 2.08 and 1.83 in the two groups, respectively.

We found an induction of RMS spherical aberration for a 6-mm pupil aperture of 0.65 µm. Although it is higher than the results published in some articles,[1,12,14] it is strongly comparable to the four-fold induction of absolute value of corneal spherical aberration with a 6-mm diameter encountered by Nanba et al.[15] when they investigated the aberrations after LASIK for a sample of hyperopic patients with a mean preoperative spherical equivalent of +3.66 D. Spherical aberration plays an important role in image formation under low luminance conditions such as night driving. In hyperopic eyes, LASIK involves a shift in the spherical aberration sign from positive to negative, as shown in the current study. Although the positive spherical aberration of the cornea is compensated for by negative spherical aberration in the internal optics during youth,[16] the spherical aberration in the internal optics becomes positive with aging, probably due to the age-related changes in the crystalline lens.[17,18] Thus, the corneal spherical aberration changing from a positive to negative value after hyperopic LASIK may have different effects on the visual function, depending on the patient's age. The induction of negative spherical aberration after hyperopic surgery increases the depth of field and improves the near vision. Therefore, this induction of spherical aberration could be a benefit, especially in patients with hyperopia and presbyopia. Causes of induction of spherical aberrations might be stromal bed hydration, creation of the flap, biomechanical responses, and epithelial remodeling after LASIK.[19-21]

Regarding the RMS for coma and coma-like aberrations for the 6-mm pupil aperture, we found a statistically significant induction when comparing the preoperative and postoperative period. Other studies have also reported results in which an increase in the RMS coma and radial aberrations exist.[1,12-14] An important factor might be that the treatment was centered on the

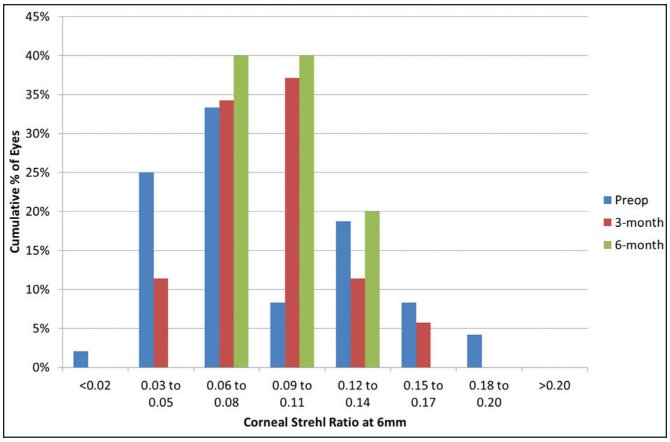

Figure 5. Histogram of preoperative and postoperative Strehl ratio.

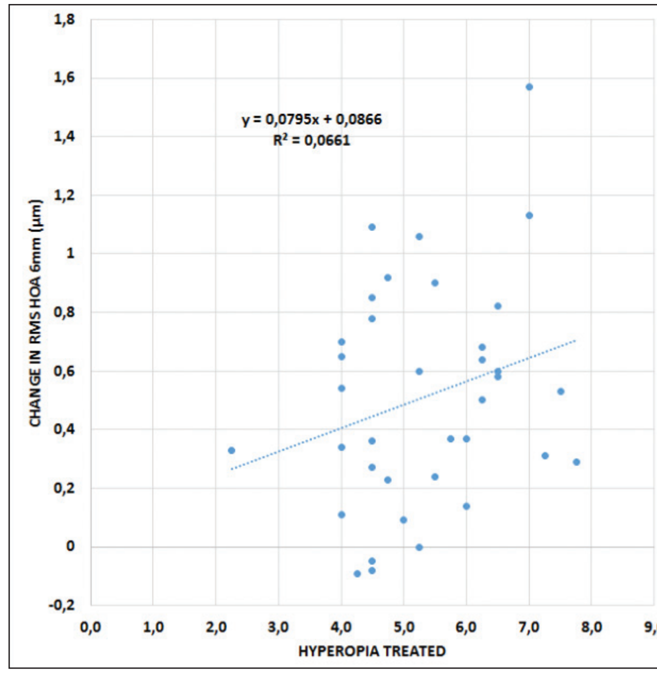

Figure 6. Linear regression model between the hyperopia treated and the difference between preoperative and postoperative root mean square higher order aberrations (RMS HOA) for a 6-mm pupil.

entrance pupil center. It is known that patients with hyperopia tend to have a large angle kappa, and therefore the distance between the corneal vertex and the entrance pupil center would have been significant in the majority of eyes. In this study, the hyperopic LASIK treatments were centered in the pupil center instead of the corneal vertex. It could be possible that the corneal vertex centration improved the results obtained in this study.[22-26] In this study, the quality of vision or night vision complaints was not evaluated using questionnaires. Future studies are required to know the subjective effect of this increase in aberrations.

A statistically significant decrease was found in relation to the corneal asphericity during the postoperative period when we measured both diameters (4.5 and 8 mm), which is consistent with other published studies.[27-29] It is well known that the change to a more prolate anterior corneal surface (eg, the one that hyperopic LASIK induces) will play a major role in decreasing anterior corneal asphericity, which also contributes to negative primary spherical aberration, thus decreasing the optical quality of the eye. For this reason, several ablation profiles (wavefront optimized, Q factor, Q optimized, and asphericity preserving) have been designed to maintain or at least try to control the final corneal asphericity following the procedure. It is important to clarify that the aspheric aberration-neutral ablation profile, used by the Amaris excimer laser platform to conduct the treatments, is intended to balance the induction of corneal aberrations and not corneal asphericity, trying to preserve the preoperative corneal aberrations of the patient.[28] Indeed, even when spherical aberration and corneal asphericity are related, this does not mean that controlling the amount of corneal asphericity induced by treatment will maintain the spherical aberration.[29] Some studies[30] in the literature have proven the advantages of using optimized and customized ablation profiles because these studies report less induction of corneal HOAs when comparing optimized ablation profiles versus standard ablation profiles.

The fact that we chose to center the ablation on the entrance pupil center instead of the corneal vertex could explain our slightly higher percentage of eyes losing two lines of CDVA compared to hyperopic treatments in a similar range with a similar technology (ie, small, high-speed flying spots) and optimized ablation profiles with large optical zone designs and transition zones.[23-25] Our enhancement rate (29.4%) is greater than that after myopic LASIK (approximately 3% to 10%).[31] However, it is comparable to the general rate in hyperopic LASIK of between 20% and 30%.[32] No vision-threatening complications occurred after the enhancement procedure in any eye.

Several techniques were developed for the hyperopia correction, but the outcomes obtained were poor.[33-37] Clear lens extraction is less accurate and predictable for hyperopia less than +3.00 D and as a treatment of high hyperopia it raises concerns about its irreversibility and loss of accommodation. Furthermore, it can produce cystoid macular edema and retinal detachment, so it is primarily reserved for patients older than 45 years or those with some degree of lens opacification.[38] Although effective, the use of phakic intraocular lens implantation for hyperopia carries the risks of intraocular complications.[39,40] High plus intraocular lenses, which are required for hyperopia, are known to induce large amounts of HOAs. Furthermore, small decentrations of these lenses induce a large amount of coma.[41-43] Future studies are required to compare the induction of HOAs between the correction of high hyperopia through LASIK and intraocular lenses to assess which technique induces more HOAs.

We may conclude that outcomes of the SCHWIND Amaris laser for treatment of high hyperopia with large optical zone and pupil center centration produce good clinical outcomes with induction of HOAs. Future challenges to be solved are the control of the induction of HOAs by providing better ablation profiles, as well as the control of decentration by providing a more accurate centration reference and more advanced eye tracking systems. Further studies are needed to determine whether corneal vertex centration might improve outcomes of hyperopic LASIK. These challenges need to be resolved to further improve the correction of high levels of hyperopia with excimer laser surgery.

AUTHOR CONTRIBUTIONS

Study concept and design (AE, JLA); data collection (ABP-P, AE, DW-D, AAA, JLA); analysis and interpretation of data (ABP-P, SA-M); writing the manuscript (AE, DW-D); critical revision of the manuscript (ABP-P, SA-M, AAA, JLA); statistical expertise (ABP-P); administrative, technical, or material support (AE); supervision (ABP-P, SA-M, JLA)

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TABLE A

Anterior Corneal Aberrations for 5-mm Pupil Diameter[a]

Parameter	Preoperative	3 Months Postoperative	6 Months Postoperative	P[b]
RMS total (μm)	1.19 ± 0.53 (0.39 to 2.37)	1.54 ± 0.64 (0.44 to 3.28)	1.67 ± 0.80 (0.69 to 3.27)	.005
Zernike coefficient (Z^4_0) (μm)	-0.11 ± 0.03 (-0.18 to 0.02)	-0.12 ± 0.10 (-0.42 to 0.04)	-0.24 ± 0.12 (-0.51 to 0.01)	< .01
Zernike coefficient (Z^3_{+1}) (μm)	0.03 ± 0.19 (-0.27 to 0.38)	0.11 ± 0.27 (-0.46 to 0.62)	0.09 ± 0.26 (-0.52 to 0.71)	< .01
Zernike coefficient (Z^3_{-1}) (μm)	0.03 ± 0.10 (-0.20 to 0.32)	-0.08 ± 0.24 (-0.70 to 0.42)	-0.30 ± 0.25 (-0.65 to 0.02)	.154
RMS AST (μm)	0.94 ± 0.56 (0.13 to 2.06)	0.87 ± 0.38 (0.26 to 1.67)	0.82 ± 0.39 (0.29 to 1.44)	.712
RMS residual (μm)	0.17 ± 0.07 (0.08 to 0.50)	0.29 ± 0.08 (0.11 to 0.48)	0.38 ± 0.25 (0.12 to 1.20)	< .01
RMS spherical-like (μm)	0.15 ± 0.05 (0.08 to 0.42)	0.21 ± 0.08 (0.07 to 0.47)	0.35 ± 0.19 (0.16 to 0.95)	.003
RMS coma-like (μm)	0.26 ± 0.08 (0.13 to 0.51)	0.44 ± 0.15 (0.19 to 0.87)	0.53 ± 0.27 (0.21 to 0.99)	< .01
RMS HOA (μm)	0.30 ± 0.08 (0.16 to 0.54)	0.50 ± 0.15 (0.20 to 0.94)	0.65 ± 0.27 (0.41 to 0.37)	< .01

RMS = root mean square; AST = astigmatism; HOA = higher order aberrations
[a]Values are given as mean ± standard deviation (range). All aberrations are anterior.
[b]Preoperative to 3 months.

TABLE B

Anterior Corneal Aberrations for 4-mm Pupil Diameter[a]

Parameter	Preoperative	3 Months Postoperative	6 Months Postoperative	P[b]
RMS total (μm)	0.81 ± 0.49 (0.23 to 3.10)	0.91 ± 0.37 (0.31 to 1.71)	0.94 ± 0.42 (0.44 to 1.81)	.115
Zernike coefficient (Z^4_0) (μm)	-0.05 ± 0.02 (-0.19 to 0.01)	-0.02 ± 0.42 (-0.12 to 0.07)	-0.05 ± 0.05 (-0.20 to 0.02)	< .01
Zernike coefficient (Z^3_{+1}) (μm)	0.18 ± 0.11 (-0.19 to 0.36)	0.05 ± 0.10 (-0.13 to 0.32)	0.05 ± 0.10 (-0.09 to 0.33)	.120
Zernike coefficient (Z^3_{-1}) (μm)	0.02 ± 0.08 (-0.13 to 0.39)	0.02 ± 0.19 (-0.34 to 0.83)	-0.09 ± 0.15 (-0.35 to 0.11)	.078
RMS AST (μm)	0.62 ± 0.37 (0.08 to 1.43)	0.53 ± 0.23 (0.21 to 1.06)	0.53 ± 0.27 (0.14 to 0.98)	.324
RMS residual (μm)	0.12 ± 0.09 (0.05 to 0.66)	0.17 ± 0.05 (0.06 to 0.30)	0.21 ± 0.10 (0.10 to 0.47)	.002
RMS spherical-like (μm)	0.09 ± 0.05 (0.04 to 0.37)	0.10 ± 0.03 (0.03 to 0.21)	0.13 ± 0.07 (0.08 to 0.40)	.205
RMS coma-like (μm)	0.17 ± 0.19 (0.08 to 1.48)	0.23 ± 0.08 (0.10 to 0.45)	0.27 ± 0.12 (0.13 to 0.51)	< .01
RMS HOA (μm)	0.20 ± 0.20 (0.10 to 1.53)	0.26 ± 0.08 (0.10 to 0.50)	0.31 ± 0.12 (0.17 to 0.53)	< .01

RMS = root mean square; AST = astigmatism; HOA = higher order aberrations
[a]Values are given as mean ± standard deviation (range). All aberrations are anterior.
[b]Preoperative to 3 months.