Lasik for Hyperopia Using an Aberration-Neutral Profile With an Asymmetric Offset Centration

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ABSTRACT

PURPOSE: To investigate refractive outcomes and induction of corneal higher order aberrations (HOAs) in eyes with large pupil to corneal vertex offset that underwent LASIK for hyperopia using an aberration-neutral profile with corneal vertex centration and asymmetric offset.

METHODS: In this retrospective consecutive review, 26 patients (46 eyes) who underwent LASIK performed by one surgeon using the AMARIS 750S excimer laser platform and Carriazo-Pendular microkeratome (both from SCHWIND eye-tech-solutions, Kleinostheim, Germany) for flap creation were retrospectively analyzed. Only eyes targeted for plano and with a pupil to corneal vertex offset greater than 200 µm were included. The preoperative metrics were correlated with the outcomes at 3 and 6 months postoperatively.

RESULTS: The mean spherical equivalent was +3.43 ± 1.30 diopters (D) preoperatively and +0.21 ± 0.61 D at last postoperative visit ($P < .0001$). Mean refractive astigmatism was $1.09 ± 1.06$ D preoperatively, and $0.39 ± 0.43$ D at last postoperative visit. Postoperative uncorrected distance visual acuity of 20/25 or better was achieved in 74%, 65%, and 79% of eyes at 1, 3, and 6 months, respectively, compared to 85% corrected distance visual acuity of 20/25 or better preoperatively. Statistically significant correlation was observed between preoperative and postoperative aberation values for vertical trefoil ($P < .0005$), vertical coma ($P < .0005$), oblique trefoil ($P < .0001$), secondary cardinal astigmatism ($P < .05$), cardinal trefoil ($P < .05$), and secondary vertical trefoil ($P < .05$).

CONCLUSIONS: LASIK for high levels of hyperopia using corneal vertex centration with asymmetric offset was safe and predictable. Maintaining postoperative keratometry less than 49.00 D after hyperopic LASIK and centering on corneal vertex may reduce the induction of coma compared to other profiles or centration strategies.

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vertex-centered ablation group. On the other hand, in a study by Reinstein et al., the ablation centration was programmed on the coaxial light reflex. They postulated that if the centration on the coaxial light (which is similar to the vertex of the cornea) were incorrect, eyes with an offset of 0.55 mm or more should have more loss of lines. However, this was not observed in their cohort.

The asymmetric offset approach combines the strategies of both pupil centration and corneal vertex centration in a complementary manner implemented in a single treatment.

In this study, we present the refractive outcomes and induction of corneal HOAs for consecutive eyes with a pupil-to-vertex offset larger than 200 µm, which underwent LASIK for hyperopia using an aberration-neutral profile with an asymmetric offset centration. The treated population in our cohort would not be considered normal under the purview of LASIK, but our motivation with this study was to investigate the performance of asymmetric offset ablation profiles and vertex centration in cases with extreme pupil to vertex offset.

**PATIENTS AND METHODS**

In this retrospective study, 46 eyes of 26 patients (mean age: 45 ± 10.67 years; range: 18 to 62 years old) underwent LASIK by one surgeon (DdO) using the AMARIS 750S excimer laser platform (SCHWIND eye-tech-solutions, Kleinostheim, Germany) and a Carriazo-Pendular microkeratome (SCHWIND eye-tech-solutions) for flap creation. All flaps were created for an intended thickness of either 110 or 130 µm. All treatments were planned following the standard clinical practice of maintaining a postoperative keratometry less than 49.00 D. Only eyes targeted for plano and with a pupil-to-vertex offset larger than 200 µm (mean: 0.341 mm nasally and 0.001 mm inferiorly; range: 0.2 to 0.62 mm; standard error: 0.02 mm) were included in the retrospective analysis. The laser ablation was centered on the corneal vertex (subject-fixated noncoaxially sighted corneal light reflex) with an asymmetric offset centration combining pupil and corneal vertex information. The location of the corneal vertex was obtained from the Keratron Bridge topographer (Optikon, Rome, Italy); hence truly subject-fixated noncoaxially sighted corneal light reflex was used for treatment planning. Data were obtained from the topographer for the offset of the corneal vertex in relation to the pupil center (termed as chord microns in Chang and Waring). This system also accounted for the shift in pupil center due to differing pupil diameters.

**ASYMMETRIC OFFSET**

The asymmetric offset represents a method for centering ablation profiles considering pupil center and corneal vertex information simultaneously. The corneal vertex is taken as the optical axis of the ablation and the edges of the optical zone are concentric to the pupil boundaries. The use of truly subject-fixated noncoaxially sighted corneal light reflex with the AMARIS 750S excimer laser platform minimizes the possibility of a parallax error; however, this centration strategy can be generally used in laser vision correction, although subject to the implications related to the noncoaxial nature of observation.

**CORNEAL WAVEFRONT**

Corneal wavefront was measured with the Keratron Bridge topographer and reported according to International Organization for Standardization and American National Standards Institute standards for a 6-mm diameter. The left eye data were converted to right eye equivalent horizontal and oblique Zernike terms to address mirror image symmetry of eyes.

Aberration-free (SCHWIND eye-tech-solutions) ablation profiles were used in all cases. This ablation profile aims at delivering a neutral profile on the cornea. Analysis was performed for the correlation between the Zernike terms preoperatively to the Zernike terms at 3 and 6 months postoperatively. The paired Student’s t test was used to evaluate the difference between the Zernike terms.

A P value less than .05 was considered statistically significant.

**RESULTS**

**PUPIL-TO-VERTEX OFFSET**

The horizontal offset was statistically significant from zero at 0.317 ± 0.139 mm (P < .0001). The vertical offset was not statistically significant at -0.001 ± 0.118 mm (P = .50). Nonnasal offsets were rare (1 of 46 eyes with -0.052 mm temporal offset). The mean value of the length of the offset vector was 0.341 ± 0.133 mm.

Both the nasal component of the corneal vertex offset and the length of the offset vector strongly correlated with the power of the maximum hyperopic meridian (P < .0005).

**REFRACTIVE OUTCOMES**

Refractive outcomes are shown in Figure 1. Postoperative UDVA was on average -0.6 ± 0.4 (P < .0001), -0.7 ± 0.4 (P < .0001), and -0.5 ± 0.5 (P = .02) lines worse than preoperative CDVA, at 1, 3, and 6 months, respectively (Figure 1B).

No eye lost more than two Snellen lines of CDVA at any time point (Figure 1C). There was a mean loss of CDVA of -0.2 ± 0.3 lines at 1 month, which recovered to preoperative levels at 3 and 6 months of follow-up (P = .10).
Figure 1. Refractive outcomes of 46 eyes that underwent hyperopic LASIK centered on the corneal vertex using an asymmetric offset.
Undercorrection (-13%) was observed in the refractive outcomes (Figure 1D). Postoperatively, 74%, 63%, and 72% of eyes were within ±0.50 D at 1, 3, and 6 months, respectively, and 93% of eyes were within ±1.00 D at last postoperative visit (Figure 1E).

The mean spherical equivalent was +3.43 ± 1.30 D preoperatively and +0.19 ± 0.61 D 6 months postoperatively (P < .0001) (Figure 1F).

The mean refractive astigmatism was 1.09 ± 1.06 D preoperatively and 0.39 ± 0.43 D at the last postoperative visit (3 or 6 months) (P < .0001). Postoperatively 91%, 85%, and 93% of the eyes were less than 0.50 D at 1, 3, and 6 months, respectively, and 91% were less than 1.00 D at last postoperative visit (Figure 1G).

The target induced astigmatism correlated to the surgically induced astigmatism with statistical significance (P < .0001), but moderate undercorrection (-4%) was observed (Figure 1H).

A histogram of the angle of error showed that the axis of the surgically induced astigmatism was within 5 degrees of the axis of the target induced astigmatism for 59% of the eyes (Figure 11).

The correction of cardinal, oblique, and curvittal astigmatism showed statistically significant correlation (P < .0001), and a moderate undercorrection similar to the surgically induced astigmatism (Figure A, available in the online version of this article) (undercorrection curvittal surgically induced astigmatism = -5%, cardinal astigmatism = -3%, oblique astigmatism = -13%). The induction of torsional astigmatism was +0.09 ± 0.36, -0.08 ± 0.31, and 0.00 ± 0.32 D, at 1, 3, and 6 months, respectively, and remained less than 0.25 D in 93% of the cases.

**DISCUSSION**

Controversy remains regarding where to center corneal refractive procedures to maximize the visual outcomes. A misplaced refractive ablation might result in undercorrection and other undesirable side effects. Mainly, there are two different centration references that can be detected easily and measured with currently available technologies.

Pupil centration may be the most extensively used centration method for several reasons. The pupil boundaries are the standard references observed by the eye-tracking devices. Moreover, the entrance pupil can be well represented by a circular or oval aperture, similar to the most common ablation profiles. Centering on the pupil offers the opportunity to minimize the optical zone size due to the coherence between the boundary of the ablation profile and the optical zone size. Using a centering reference other than the pupil center, the size of the entrance pupil always needs to be respected, increasing the size of the ablation profile correspondingly.

On the other hand, it is well known that the pupil center shifts with changes in the pupil size. Moreover, the entrance pupil represents a virtual image of the real one. Therefore, a more morphological reference is advisable. The corneal vertex is the other major choice as the centration reference in different modalities. In a perfectly acquired topography, if the human optical system were truly coaxial, the corneal vertex would represent the corneal intercept of the optical axis. Despite the fact that the human optical system is not truly coaxial, the cornea is the main refractive surface. Thus, the corneal vertex represents a stable preferable morphologic reference supported by clinical results in several comparative studies.

The concept of asymmetric offset combines the benefits of these two centration methods. It facilitates the eye tracker functionality in the sense that the pupil center remains the reference for the center of the ablation and the corneal vertex is the reference for the optical axis of the ablation. This centration strategy would be of special benefit for noncoaxial eyes with large pupil centration-to corneal vertex offset (chord microns). For noncoaxial eyes, an aspheric cornea without aberrations (even without astigmatism) will show coma at the pupil area (due to the pupil displacement). Furthermore, for noncoaxial eyes an aspheric cornea without aberrations but with astigmatism will show trefoil at the pupil area (due to the pupil displacement). Therefore, our approach was to retain the aplanatic compensation between the cornea and the lens by centering the optical axis of ablation in the corneal vertex (subject-fixated noncoaxially sighted corneal light reflex), but limiting.
the modified area concentric to the pupil projection boundaries.

This approach should result in a reduced induction of asymmetric aberrations (coma and trefoil) and a two-fold reduction in the amount of corneal tissue removed compared to the oversized symmetric offset ablations, further avoiding undercorrections and nomogram adjustments due to the placement of the peak of the ablation profile at a location other than the visual axis (or a closer estimate of the visual axis).

The induction of HOAs after hyperopic LASIK is well documented. For example, Llorente et al. found that ocular HOAs increased by a factor of 2.20 and corneal HOAs increased by a factor 1.78 postoperatively. Nanba et al. found that both corneal coma-like aberrations at 6 mm and corneal spherical-like aberrations increased 182% and 223%, respectively, after hyperopic LASIK. They also found that the positive spherical aberration changed to negative spherical aberration postoperatively. Wang et al. reported similar results.

Chen et al. found that corneas became more prolate after hyperopic LASIK. This increase was highly correlated with the attempted correction. However, the increased prolate shape did not correlate with visual or refractive outcomes. Alió et al. investigated the corneal aberrations and objective visual quality after hyperopic LASIK with the ESIRIS excimer laser (SCHWIND eyesolutions). They found that the greater the hyperopic correction, the greater the induction of negative spherical aberration. The corneal asphericity at 4.5 mm became significantly more negative. This indicates that induced spherical aberration and asphericity correlated with the amount of hyperopic treatment. The postoperative root mean square of aberrations was higher in the cornea compared to the whole eye (root mean square of ocular aberrations). Alió et al. concluded that the internal optics of the eye partially compensated for the anterior corneal surface postoperatively.

The minor induction of horizontal coma in our cohort did not correlate with laser correction. If pupil centration would be an appropriate strategy for avoiding the induction of aberrations, additional coma induction correlating with refractive correction would occur for corneal vertex centration. The nasalization of the corneal vertex with respect to the topographic pupil increased with the power of the maximum hyperopic meridian at a rate of 35 µm per diopter. This is in agreement with the findings by Artal et al. and may be attributed to the shorter axial length of high hyperopic eyes.

Similar percentages of eyes achieving UDVA of 20/25 (61% at last follow-up) or better postoperatively and CDVA of 20/25 (85%) preoperatively confirm the efficacy of hyperopic treatments in our cohort. Additionally, the mean postoperative UDVA was approximately half a line worse than the mean preoperative CDVA.

Concerning safety, no eye lost more than two Snellen lines of CDVA at any time point and there was no difference in CDVA from preoperative to postoperative levels.

The postoperative visual findings were not affected by the amount of correction or the amount of offset. These findings demonstrate that the use of an asymmetric offset was not detrimental for the visual outcomes.

In terms of the refractive outcomes, we found marginal undercorrection in the sphere and cylinder corrections, with 93% of eyes within ±1.00 D and 80% with less than 0.50 D refractive astigmatism postoperatively. The results remained stable between the 3- and 6-month postoperative visits. However, in our series we still induced spherical aberration, which indicates that the induction of coma might improve by further reducing or eliminating the induction of spherical aberration.

It is noteworthy that there were several parameters affected by preoperative spherical equivalent in our series. Preoperative CDVA and postoperative UDVA were negatively affected by preoperative spherical equivalent, accounting for the loss of half a line in visual acuity per diopter of spherical equivalent. Postoperative astigmatism was negatively affected by preoperative spherical equivalent, accounting for nearly 0.10 D more of astigmatism (in particular 0.07 D extra of oblique astigmatism) per each diopter of spherical equivalent.

There are some limitations in our study. The use of 3- and 6-month postoperative data for hyperopia may be contentious to some. However, in a previous study we analyzed and differentiated hyperopic regression from latent hyperopia that will manifest postoperatively using corneal topography. In that publication we also showed that hyperopic LASIK is stable after 3 months. The use of corneal aberrations may not be indicative of ocular visual performance. However, it provides information about the optical response to ablation in the cornea and is a reliable method to document changes in HOAs. The lack of a control group can be considered a limitation of this study. A direct comparison of the outcomes of our cohort with a cohort based on vertex and pupil centration could further explore and compare the clinical benefits of each approach. Furthermore, considering the wide range of offset in our cohort (range: 0.2 to 0.62 mm), the effect of high asymmetric offset on various HOAs may be investigated distinguishing between subgroups based on the amount of decentration between vertex and pupil center. However, we did not have balanced subgroups in our cohort to make such an analysis.

Hyperopic LASIK provides smaller functional optical zones, so special caution shall be paid while designing the refractive procedure in these patients.
We have shown that LASIK for hyperopia using an aberration-neutral profile with an asymmetric offset centration is safe and predictable. Maintaining postoperative keratometry less than 49.00 D after hyperopic LASIK and centering on the corneal vertex reduces the induction of coma compared to nonaspheric profiles and lower hyperopia. The use of corneal vertex centration results in a morphologically stable cornea, less topographic asymmetry, and enhanced stability.

AUTHOR CONTRIBUTIONS
Study concept and design (SA-M, DdO); data collection (DdO); analysis and interpretation of data (SA-M, DdO); writing the manuscript (SA-M, DD); critical revision of the manuscript (DdO); supervision (DdO)

REFERENCES
Figure A. The correction of cardinal, oblique, and curvital astigmatism showed statistically significant correlations, and a moderate undercorrection \((P < .0001)\). \(D = \text{diopters}\)

Figure B. Comparison of the corneal aberrations analyzed at 6-mm diameter preoperatively and postoperatively. Hor = horizontal; Ver = vertical; ob = oblique; car = cardinal