Coaxially Sighted Corneal Light Reflex Versus Entrance Pupil Center Centration of Moderate to High Hyperopic Corneal Ablations in Eyes With Small and Large Angle Kappa

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ABSTRACT

PURPOSE: To determine whether centering ablations on the coaxially sighted corneal light reflex (CSCLR) in eyes with large angle kappa leads to poor visual outcomes when compared to patients with eyes with negligible angle kappa that by default would be centered on the entrance pupil. In eyes with no angle kappa, the CSCLR coincides with the entrance pupil center, whereas eyes with large angle kappa possess an offset between the CSCLR and the entrance pupil center.

METHODS: This study was a retrospective case series of consecutive patients treated by hyperopic LASIK using the MEL80 excimer laser (Carl Zeiss Meditec, Jena, Germany). All ablations were centered on the CSCLR using the standard non-wavefront-guided ablation profile. Angle kappa was classified according to pupil offset defined as the distance in the corneal plane between the entrance pupil center and the corneal vertex. Eyes were divided into two discrete groups according to the pupil offset: small angle kappa for pupil offset of 0.25 mm or less (n = 30) and large angle kappa for pupil offset of 0.55 mm or greater (n = 30). Safety, accuracy, cylinder vector analysis, contrast sensitivity, vertex centered corneal aberrations, entrance pupil centered whole eye aberrometry, and night vision disturbances were compared between the two groups.

RESULTS: There were no statistically significant differences in safety, accuracy, induced astigmatism, contrast sensitivity, or night vision disturbances between the two groups. There was also no statistically significant difference between groups for vertex centered corneal aberrations; however, as expected, coma was higher in the large angle kappa group for entrance pupil centered aberrometry because the treatment had been centered on the CSCLR rather than the entrance pupil center.

CONCLUSION: Refractive outcomes of high hyperopic LASIK were not found to be worse for eyes where ablation was centered more than 0.55 mm from the entrance pupil as determined by CSCLR in eyes with large angle kappa. The absence of poor quality visual outcomes in cases, which by entrance pupil centration are considered significantly “de-centered,” supports the notion that centration relative to the CSCLR may be preferable. This provides evidence that refractive corneal ablation should not be systematically aligned with the entrance pupil center.


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Submitted: October 3, 2011; Accepted: April 1, 2013

Dr. Reinstein is a consultant for Carl Zeiss Meditec (Jena, Germany) and has a proprietary interest in the Artemis technology (ArcScan Inc., Morrison, Colorado) through patents administered by the Cornell Center for Technology Enterprise and Commercialization, Ithaca, New York. The remaining authors have no financial or proprietary interest in the materials presented herein.

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doi:10.3928/1081597X-20130719-08
Food and Drug Administration trials and hence approved treatment protocols.

In 2001, Mrochen et al.3 recommended centration on the coaxially sighted corneal light reflex (CSCLR) because it bests approximates the visual axis in a theoretical analysis of the effect of decentration on higher-order aberrations. In 2002, one of the authors (DZR) presented a paper based on a population of hyperopic cases suggesting that corneal ablations should be centered on the CSCLR by comparing results of eyes with angle kappa smaller or larger than 0.25 mm where all eyes had been treated on the CSCLR and finding that sphero-cylindrical and visual outcomes were not different.6 This has been his standard routine protocol for all non–wavefront-guided ablations since 1997 for both myopia and hyperopia.

There have since been studies reporting ablations centered on the corneal vertex for hyperopic patients,7-9 myopic patients,10,11 and patients with mixed astigmatism.12 Studies comparing results between entrance pupil center and corneal vertex centration for myopic11,13 and hyperopic8,14,15 patients have reported either no difference between groups or better results in the group using corneal vertex centration. However, there are studies where entrance pupil center centration was used and reported outcomes were satisfactory; this is most likely due to the fact that the angle kappa is small in most patients,8,14,16 in which case centering on the entrance pupil center results on average in similar outcomes as corneal vertex centration. The difference in protocol for centration will result in a difference in outcomes only in the minority of eyes with a large angle kappa, but no studies have yet exclusively analyzed eyes with large angle kappa. This might explain why the question of optical zone centration remains unanswered. It is interesting to note that the debate regarding centration of intracorneal inlays has been resolved with the recommendation that intracorneal inlays be centered on the CSCLR after poor results were found in cases where the inlays were centered on the entrance pupil center.17-22

The purpose of this study was to compare outcomes of moderate to high hyperopic LASIK with the ablation centered on the CSCLR between a group of eyes with a small angle kappa and a group of eyes with a large angle kappa. Angle kappa was represented by the pupil offset, defined as the distance in the corneal plane between the entrance pupil center and the corneal vertex, measured using the Orbscan software (Bausch & Lomb, Salt Lake City, UT). The small angle kappa group was required to have a pupil offset of 0.25 mm or less and the large angle kappa group was required to have a pupil offset of 0.55 mm or greater so that the two groups represented the two extremes of small and large angle kappa. Outcome measures were safety, accuracy, astigmatism, contrast sensitivity, vertex corneal and entrance pupil center whole eye wavefront, and subjective night vision. The small angle kappa group was used as the control group because a similar result would be achieved using either entrance pupil center centration or corneal vertex centration given that the pupil offset was no greater than 0.25 mm. On the other hand, centering the ablation on the CSCLR in the large

PATIENTS AND METHODS

This study was a retrospective case series collected from consecutive patients treated with hyperopic LASIK at the London Vision Clinic, London, United Kingdom, between May 2004 and June 2007. All treatments were performed as bilateral simultaneous LASIK by a single surgeon (DZR). Participants gave their informed consent for the use of their data for research, analysis, and publication purposes.

STUDY DESIGN

This study set out to compare the outcome of moderate to high hyperopic LASIK with the ablation centered on the CSCLR between a group of eyes with a small angle kappa and a group of eyes with a large angle kappa. Angle kappa was represented by the pupil offset, defined as the distance in the corneal plane between the entrance pupil center and the corneal vertex, measured using the Orbscan software (Bausch & Lomb, Salt Lake City, UT). The small angle kappa group was required to have a pupil offset of 0.25 mm or less and the large angle kappa group was required to have a pupil offset of 0.55 mm or greater so that the two groups represented the two extremes of small and large angle kappa. Outcome measures were safety, accuracy, astigmatism, contrast sensitivity, vertex corneal and entrance pupil center whole eye wavefront, and subjective night vision. The small angle kappa group was used as the control group because a similar result would be achieved using either entrance pupil center centration or corneal vertex centration given that the pupil offset was no greater than 0.25 mm. On the other hand, centering the ablation on the CSCLR in the large
angle kappa group meant that the ablation was decen-
tered by at least 0.55 mm relative to the entrance pupil
center for all eyes.

Other inclusion criteria were as follows: medically suit-
able for LASIK, manifest refractive error in the minimum
hyperopic meridian of +2.50 diopters (D) or greater (to ac-
centuate any decentration effects), refractive astigmatism
of 2.00 D or less, age younger than 60 years, and corrected
distance visual acuity (CDVA) of 20/25 or better.

The aim was to obtain two groups (small and large
angle kappa) of 30 eyes matched for minimum hyper-
opic meridian and CDVA. To ensure that the groups
were distributed evenly for minimum hyperopic meri-
dian, eyes were divided into three refractive bins with
the intention of including 10 eyes in each refractive
bin for both groups. Refractive bins were defined as
a minimum hyperopic meridian of +2.50 D or greater
and less than +3.50 D, +3.50 D or greater and less than
+4.50 D, and +4.50 D or greater and +5.50 D or less. For
each refractive bin, pupil offset was measured for con-
secutive eyes until 10 eyes were found with pupil off-
set of 0.25 mm or less (for the small angle kappa group)
and 10 eyes were found with pupil offset of 0.55 mm or
greater (for the large angle kappa group).

Preoperative Assessment. A full ophthalmologic
examination was performed on all patients prior to sur-
egery, including manifest refraction, topography (Atlas
995; Carl Zeiss Meditec, Jena, Germany), and whole eye
wavefront assessment (WASCA aberrometer; Carl Zeiss
Meditec). The whole eye wavefront (entrance pupil cen-
ter aberrometry) was obtained after tropicamide 1% cyc-
cloplegia so that data were available for a 6-mm analysis
zone centered on the entrance pupil center. However,
because the ablations were centered on the CSCLR, the
entrance pupil center aberrations were not aligned with
the treatment in the large angle kappa group. Due to the dif-
fERENCE in alignment between the treatment and the aber-
rometer measurement, any spherical aberration induced
symmetrically about the treatment center would be mea-
sured as coma on entrance pupil center aberrometry. To
assess the change in aberrations due to the ablation, we
also needed to obtain a wavefront measurement centered
on the CSCLR. Ideally, we would have recalculated the
entrance pupil center aberrometry measurement using
the CSCLR as the center, but this was not possible with
the current software. Instead, the corneal elevation data
obtained from the Atlas were imported into VOLPro
(Sarver and Associates; Carbondale, IL) to calculate the
corneal wavefront aberrations. The corneal wavefront
calculation was centered on the corneal vertex (as the
closest approximation of the CSCLR) over a 6-mm analy-
sis zone irrespective of the pupil boundary because the
option to restrict the analysis to be within the pupil was
not available in the VOLPro software. Coma, spherical
aberration, and higher-order root mean square (HORMS)
aberrations were calculated using Optical Society of
America notation for both entrance pupil center whole
eye aberrometry and vertex centered corneal wavefront.

The disadvantage of having entrance pupil center whole
eye aberrometry and vertex centered corneal wavefront
was that the magnitude of aberrations could not be com-
pared between the two methods of measurement.

CDVA, uncorrected distance visual acuity (UDVA),
and contrast sensitivity were assessed with the CSV-
1000 ETDRS chart (VectorVision Inc., Greenville, OH).

Surgery. All patients underwent LASIK using the
MEL80 excimer laser (Carl Zeiss Meditec) and Hansa-
tome zero compression microkeratome (Bausch &
Lomb, St. Louis, MO).

The standard non–wavefront-guided MEL80 aberra-
tion smart ablation (ASA) profile was used in all cases.
A true optical zone of 7 mm was used in all eyes that
included a transition zone of 2 mm. The corneal ab-
lation was centered on the coaxially sighted corneal
light reflex (CSCLR). During surgery, the CSCLR was
determined before the flap was lifted as the first Pur-
kinje reflex, seen as the patient fixated coaxially with
the aiming beam and the view of the surgeon’s con-
tralateral eye through the operating microscope. The
CSCLR was used as the best approximation of the in-
tersection of the visual axis with the cornea.

Postoperative Evaluation. Patients were observed
at 1 day and 1, 3, 6, and 12 months postoperatively.
UDVA, manifest refraction, and CDVA were obtained
at all visits after 1 day. Atlas topography, WASCA aber-
rometry, and contrast sensitivity were performed and
night vision quality was assessed using the Surgical
Eyes Visual Effects Simulator (Adam Bogart, Toronto,
Canada) at 3 and 12 months postoperatively. Night vi-
sion disturbances were classified as none, slight, mild,
moderate, and severe. The patient’s subjective symp-
toms were compared with the change in aberrations
for both entrance pupil center aberrometry and vertex
centered corneal wavefront to investigate which type
was more representative of the patient’s perception.

Statistical Analysis
The outcomes were analyzed for the primary treat-
ment data only. Data from the most recent visit were
used for analysis. Safety and accuracy were reported
according to the Waring Standard Graphs. The astig-
matism analysis was performed according to the Al-
pins method. Efficacy analysis was excluded because
a significant proportion of eyes were not intended for
plano refraction. All eyes were included for cylinder
vector analysis. Mesopic contrast sensitivity was con-
vereted into log values before calculating all statistics. The mean normalized mesopic contrast sensitivity ratio was calculated.\textsuperscript{25} Student’s \( t \) tests were used to compare data between groups. The chi-square test was used to compare night vision quality between groups. Microsoft Excel 2007 (Microsoft Corporation, Redmond, WA) was used for data entry and statistical analysis.

## RESULTS

### POPULATION

The population demographics are reported in Table 1 for both groups. The distribution of the pupil offset in the population is shown in Figure 2.

The average follow-up was 12.6 ± 3.9 months (range: 3.2 to 26.4 months) in the small angle kappa group (90\% at 12 months) and 11.3 ± 4.1 months (range: 3.7 to 21.2 months) in the large angle kappa group (77\% at 12 months). All eyes with less than 12 months of follow-up had undergone a re-treatment before 12 months, having had a stable refraction (within 0.25 D for sphere and cylinder) 2 months apart.

### ACCURACY

The accuracy histogram is shown in Figure 3. There was no statistically significant difference between groups (\( P = .797 \)).

### SAFETY

Safety outcomes are shown in Figure 4. There was no statistically significant difference in safety between groups (\( P = .278 \)).

### ASTIGMATISM

The refractive astigmatism treated was statistically significantly greater in the large angle kappa group (target induced astigmatism = 0.91 ± 0.55 D) than in the small angle kappa group (target induced astigmatism = 0.62 ± 0.48) (\( P = .032 \)). However, there was no statistically significant difference (\( P = .735 \)) in the difference vector postoperatively (0.78 ± 0.56 for the small angle kappa group and 0.84 ± 0.75 for the large angle kappa group).

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### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Small Angle Kappa</th>
<th>Large Angle Kappa</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. (eyes)</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Minimum hyperopic meridian (D)</td>
<td>+3.85 ± 0.98 (+2.50 to +5.50)</td>
<td>+3.87 ± 0.90 (+2.50 to +5.50)</td>
<td>.917</td>
</tr>
<tr>
<td>Attempted SEQ (D)</td>
<td>+4.15 ± 1.1 (+2.50 to +5.88)</td>
<td>+4.33 ± 0.89 (+2.75 to +5.75)</td>
<td>.055</td>
</tr>
<tr>
<td>CDVA</td>
<td>93% eyes = 20/20, 7% eyes = 20/25</td>
<td>93% eyes = 20/20, 7% eyes = 20/25</td>
<td>.349</td>
</tr>
<tr>
<td>Pupillary offset (mm)</td>
<td>0.17 ± 0.05 (0.05 to 0.25)</td>
<td>0.69 ± 0.10 (0.55 to 0.88)</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Scotopic pupil size (mm)</td>
<td>5.47 ± 1.00 (3.04 to 7.66)</td>
<td>5.08 ± 1.07 (3.04 to 6.86)</td>
<td>.141</td>
</tr>
<tr>
<td>Treatment zone (mm)</td>
<td>6.97 ± 0.18 (6.00 to 7.00)</td>
<td>6.98 ± 0.10 (6.50 to 7.00)</td>
<td>.827</td>
</tr>
<tr>
<td>Accuracy of SEQ relative to intended target (D)</td>
<td>+0.40 ± 0.78 (-1.38 to +2.29)</td>
<td>+0.45 ± 0.74 (-1.13 to +1.87)</td>
<td>.797</td>
</tr>
</tbody>
</table>

\( D = \) diopters; \( SEQ = \) spherical equivalent refraction; \( CDVA = \) corrected distance visual acuity

\( a \) Values are mean ± standard deviation (range).
CONTRAST SENSITIVITY

Table 2 presents the normalized mesopic contrast sensitivity data. There was no statistically significant difference ($P > .05$) in the change in contrast sensitivity between the small and large angle kappa groups at the 6, 12, and 18 cpd frequencies. However, at 3 cpd, the difference was statistically significant with a slight loss of contrast in the small angle kappa group and a slight gain of contrast in the large angle kappa group.

VERTEX CENTERED CORNEAL WAVEFRONT

The mean level of corneal aberrations and the mean change for coma, spherical aberration, and HORMS are presented in Table 3. There was no statistically significant difference in the change in higher-order aberrations between groups ($P > .474$).

ENTRANCE PUPIL CENTERED WHOLE EYE ABERROMETRY

The mean level of whole eye aberrations and the mean change for coma, spherical aberration, and HORMS are presented in Table 3. As expected, the change in HORMS and in coma was statistically significantly greater in the large angle kappa group than in the small angle kappa group ($P = .001$ for HORMS; $P = .004$ for coma). There was no statistically significant difference in the change in spherical aberration between groups ($P = .600$).

NIGHT VISION DISTURBANCES

Night vision disturbances are reported in Table A (available in the online version of this article). There was no statistically significant difference between groups ($P = .859$).

DISCUSSION

This study demonstrated that there were no statistical differences in refractive outcomes or night vision disturbances after moderate to high hyperopic LASIK centered on the CSCLR between eyes with a small angle kappa and eyes with a large angle kappa. This study of course does not prove that the results would have been worse in the large angle kappa group had the treatments been centered on the entrance pupil center. However, the large angle kappa group (with a minimum pupil offset of 0.55 mm) was selected because the eyes would be the most at risk of ablation decentration and the associated visual symptoms according to the entrance pupil center centration hypothesis, and this study population only included eyes with a minimum hyperopia of +2.50 D to potentiate the possible detrimental effect of not centering on the entrance pupil and the resultant decentration effects. The fact that the results were similar between the small and large angle kappa groups therefore provides evidence against the entrance pupil center centration hypothesis and supports the CSCLR centration hypothesis.

The ideal study design to answer the question would have been to select a group of eyes with a large angle kappa and randomly select the center of the ablation, entrance pupil center, or CSCLR and compare outcomes between groups. However, we believed that this study design would be difficult to justify because, by definition, half of the eyes would suffer from a de-centered ablation and therefore poorer outcomes.

Although centration of corneal refractive procedures over the entrance pupil center has been accepted as the...
standard for many years, there is mounting evidence that this might not be the optimal choice, not least because the position of the entrance pupil center varies according to pupil size as lighting conditions change.16

One other factor is that neural processing of nascent aberrations leads to an aberration-free perceived image in most people. If the treatment is centered somewhere other than the visual axis, then the aberrations will be made asymmetric about the visual axis and of a completely different type. Neural processing systems that are already in place will not filter this new, shifted optical vertex. This has been partly demonstrated by Artal et al.,26 who showed that vision was degraded simply by rotating the nascent aberrations. Therefore, the most logical approach appears to be one where aberrations are changed symmetrically about the same axis that the patient presents with rather than minimizing aberrations based on a different center.

Because the CSCLR is the closest approximation to the visual axis,5 the center of the optical system is maintained by centering the ablation on the CSCLR. In hyperopia, patients have on average larger angle kappa than in myopia27; therefore, if treated based on the entrance pupil center, the shift of the new postoperative vertex from the original vertex position is further from the optical geometry of the nascent eye and is more likely to induce topographic decentration and symptoms of night vision disturbances. The creation of a new vertex is likely to have more impact on a post-hyperopic LASIK cornea than a myopic-treated cornea because the rate of change in curvature near the vertex is greater after hyperopic ablations where the cornea has been steepened. Results from the current study agree with previous publications demonstrating that CSCLR centration is safe and leads to excellent visual outcomes and well-centered postoperative corneal topographies.8 It is also worth noting that many corneal inlay models are now recommended to be centered on the corneal reflex.17-22

There are two commonly used methods of determining the location of the visual axis; either the CSCLR is used as determined by the surgeon intraoperatively or the topographic decentration in the corneal plane between the entrance pupil center and the corneal vertex is measured and entered into the laser software program of some systems.9 Using the topographic corneal vertex location has some advantages because this point is reliable and reproducible on topography, whereas there can be some inter-individual differences in the location of the first Purkinje reflex. Although the CSCLR is, on average, the best approximation of the corneal intercept of the visual axis, this will not be the case for all eyes. Based on the Pande and Hillman5 data of the average location of the visual axis, CSCLR, and entrance pupil center, we calculated that the CSCLR was within ±0.25 mm of the visual axis in 60% of eyes, whereas the entrance pupil center was within ±0.25 mm of the visual axis in only 32% of eyes. This means that there are some cases where some decentration will still occur when the ablation is centered on the CSCLR and some cases where the entrance pupil center will be closer to the visual axis than the CSCLR.

Location of the center of the treatment zone is particularly relevant when using wavefront-guided ablations. Wavefront is conventionally calculated with reference to the entrance pupil center because whole

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### TABLE 3

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Small Angle Kappa Before Surgery</th>
<th>After Surgery</th>
<th>Change</th>
<th>Large Angle Kappa Before Surgery</th>
<th>After Surgery</th>
<th>Change</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corneal aberrations</td>
<td>0.398 ± 0.127</td>
<td>0.676 ± 0.230</td>
<td>0.291 ± 0.213</td>
<td>0.415 ± 0.139</td>
<td>0.954 ± 0.288</td>
<td>0.539 ± 0.319</td>
<td>.001</td>
</tr>
<tr>
<td>HORMS (µm)</td>
<td>0.909 ± 0.306</td>
<td>0.256 ± 0.329</td>
<td>0.364 ± 0.178</td>
<td>0.649 ± 0.320</td>
<td>0.284 ± 0.312</td>
<td>0.682</td>
<td></td>
</tr>
<tr>
<td>Coma (µm)</td>
<td>0.335 ± 0.169</td>
<td>0.320 ± 0.349</td>
<td>0.364 ± 0.178</td>
<td>0.649 ± 0.320</td>
<td>0.284 ± 0.312</td>
<td>0.682</td>
<td></td>
</tr>
<tr>
<td>Spherical aberration (µm)</td>
<td>0.256 ± 0.083</td>
<td>-0.142 ± 0.222</td>
<td>-0.398 ± 0.222</td>
<td>0.189 ± 0.090</td>
<td>-0.173 ± 0.190</td>
<td>-0.362 ± 0.160</td>
<td>.474</td>
</tr>
<tr>
<td>Whole eye aberrations</td>
<td>0.255 ± 0.150</td>
<td>-0.237 ± 0.191</td>
<td>-0.462 ± 0.227</td>
<td>0.237 ± 0.133</td>
<td>-0.253 ± 0.221</td>
<td>-0.490 ± 0.185</td>
<td>.600</td>
</tr>
</tbody>
</table>

HORMS = higher-order root mean square

*Change between the two groups; significant values indicated in bold.

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Journal of Refractive Surgery • Vol. 29, No. 8, 2013
eye aberrometry-based wavefront data can only be obtained within the pupil. However, in eyes with a large angle kappa, aberrations measured with reference to the entrance pupil center will be different from aberrations measured with reference to the corneal vertex because of the offset between the two locations in the corneal plane. For example, for an eye with a large pupil offset, spherical aberration measured with reference to the entrance pupil center will result in coma when measured with reference to the corneal vertex. Because almost all whole eye aberrometers measure aberrations with reference to the entrance pupil center (and not the corneal vertex), aberrations resulting from ablation profiles centered on the CSCLR will not truly represent how the aberrations induced by the ablation are perceived by the patient.

The difference between vertex centered corneal wavefront and whole eye pupil-centered wavefront was demonstrated in this study as expected where the coma was greater on entrance pupil center aberrometry in the large angle kappa treated group due to the offset between the center of the measurement and the treatment center. The spherical aberration was similar in both groups, which can be explained by the fact that spherical aberration is a field independent aberration, meaning that the spherical aberration value is the same irrespective of the location of the analysis zone, whereas coma is a field-dependent aberration. The HORMS was also greater in the large angle kappa group but, as with the coma, the difference would probably be less if the aberrations were calculated centered on the corneal vertex because this would align the wavefront with the center of the ablation and with the symmetrically induced aberrations as demonstrated by the similarity between groups for corneal aberrations. However, the aberrations experienced by the patient are influenced by the pupil boundary. In the large angle kappa group, a proportion of the ablation was done outside the edge of the pupil, which would result in asymmetric aberrations inside the pupil boundary; an increase in on-axis spherical aberration will in this case result in perceived increased coma due to the cropping effect of the pupil. Thus, an increase in corneal spherical aberration about the nascent visual axis results in an increase in coma for the retinal image. Conversely, had an eye with a large angle kappa been treated on the entrance pupil center, a new vertex would have been created, which would induce coma away from the nascent visual axis of that eye and therefore, presumably, also have a detrimental effect on vision. Further study, possibly using adaptive optics systems, is needed to study eyes with large angle kappa and correlate the patients’ perceived image with the increases in coma either on or off the visual axis.

Despite the relative increase in whole eye higher-order aberrations, the large angle kappa group was not found to have increased night vision disturbance complaints or reduced contrast sensitivity. This result provides evidence that the patient is therefore capable of neurally processing the induced aberrations. This is most likely because the patients in the large angle kappa group already had coma preoperatively (mean coma was 0.25 μm in the large angle kappa group compared to 0.18 μm in the small angle kappa group) caused by the fact that the pupil was not aligned with the CSCLR. Therefore, these patients are naturally adapted to coma in this orientation, meaning that neural processing had already developed to filter aberrations of this type. Although induction of a certain amount of coma would seem to be unavoidable in eyes with a large angle kappa, at least it will be on axis for the patient’s neurally adapted visual system and thus counterbalanced by the natural neural processing of nascent aberrations.

On the other hand, the increase in corneal wavefront coma and higher-order aberrations observed were similar in both groups, which demonstrates that the laser ablation induced similar aberrations in both groups (as would be expected). The postoperative night vision disturbances and contrast sensitivity were also observed to be similar in both groups. This demonstrates an agreement between the patient’s perceived image and the postoperative corneal wavefront; if the patient’s perceived image had been better correlated to the whole eye wavefront, the night vision disturbances would have been expected to be worse in the large angle kappa group (although this is based on corneal wavefront calculated over a 6-mm diameter irrespective of the pupil boundary, so the corneal wavefront actually affecting the light that reaches the retina may be different then the data used here). We believe these findings suggest that a wavefront measurement centered on the corneal vertex in a patient with a large pupil offset may better represent what the patient sees cortically compared with a wavefront measurement centered on the entrance pupil center.

Optical zone size is another important issue to consider when centering the treatment on the CSCLR in patients with a large angle kappa. Because the treatment is not aligned with the entrance pupil center, there is the possibility that the optical zone will not be completely covered by the pupil if the pupil is large, which could lead to increased coma. In the current study, the optical zone used was 7 mm with a 2-mm transition zone, whereas the maximum dark pupil diameter was 7.9 mm and was greater than 7 mm in only 2 eyes (7%).

Finally, the results of the current study may only apply to hyperopic treatments using the MEL80 ex-
cimer laser due to differences in ablation profile design, although similar results have been reported using other excimer laser systems where the treatment has been centered on the CSCLR or corneal vertex.\textsuperscript{11,13-15} The current study found similar refractive outcomes visual quality and subjective night vision between a group of eyes with a small angle kappa and a group of eyes with a large angle kappa after moderate to high hyperopic LASIK where the ablation was centered on the CSCLR. This provides evidence to support the hypothesis that ablations should be centered on the visual axis (or closest approximation).

**AUTHOR CONTRIBUTIONS**

Study concept and design (DZR, MG, TJA); data collection (MG, TJA); analysis and interpretation of data (DZR, MG, TJA); drafting of the manuscript (DZR, MG); critical revision of the manuscript (DZR, TJA)

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### Table A

#### Night Vision Disturbances After LASIK

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>None</th>
<th>Slight</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small angle kappa</td>
<td>67%, n = 20/30</td>
<td>27%, n = 8/30</td>
<td>7%, n = 2/30</td>
<td>0%, n = 0/30</td>
<td>0% n = 0/30</td>
</tr>
<tr>
<td>Large angle kappa</td>
<td>70%, n = 21/30</td>
<td>23%, n = 7/30</td>
<td>0%, n = 0/30</td>
<td>7%, n = 2/30</td>
<td>0%, n = 0/30</td>
</tr>
</tbody>
</table>