Optical Zone Enlargement and Recentration After Previous Myopic LASIK by Topography-guided Custom Ablation

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ABSTRACT

PURPOSE: To report the visual and refractive outcomes, optical zone enlargement, and recentration using topography-guided CRS-Master TOSCA II software with the MEL 80 excimer laser (Carl Zeiss Meditec AG, Jena, Germany) after primary myopic laser refractive surgery.

METHODS: Retrospective analysis of 73 eyes (40 patients) with complaints of night vision disturbances due to either a decentration or small optical zone following a primary myopic laser refractive surgery procedure using the MEL 80 laser. Multiple ATLAS topography scans were imported into the CRS-Master software for topography-guided ablation planning. The topography-guided re-treatment procedure was performed as either a LASIK flap lift, a new LASIK flap, a side cut only, or photorefractive keratectomy. Axial curvature maps were analyzed using a fixed grid and set of concentric circles superimposed to measure the topographic optical zone diameter and centration. Follow-up was 12 months.

RESULTS: The optical zone diameter was increased by 11% from a mean of 5.65 to 6.32 mm, with a maximum change of 2 mm in one case. Topographic decentration was reduced by 64% from a mean of 0.58 to 0.21 mm. There was a 44% reduction in spherical aberration, 53% reduction in coma, and 39% reduction in total higher order aberrations. A subjective improvement in night vision symptoms was reported by 93%. Regarding efficacy, 82% of eyes reached 20/20 and 100% reached 20/32 (preoperative CDVA was 20/20 or better in 90%). Regarding safety, no eyes lost two lines of CDVA and 27% gained one line. Regarding predictability, 71% of re-treatments were within ±0.50 diopters.

CONCLUSIONS: Topography-guided ablation was effective in enlarging the optical zone, centering the optical zone, and reducing higher order aberrations. Topography-guided custom ablation appears to be an effective method for re-treatment procedures of symptomatic patients after myopic LASIK.

[Ablation-related complications following refractive surgery such as decentered ablations, small optical zones, or irregular ablations can produce irregular optics and compromise quality of vision. Over the past two decades, several excimer laser platforms have developed topography-guided treatments to treat corneal irregularities. Published reports to date have found topography-guided treatment in general to be effective, successfully increasing uncorrected distance visual acuity (UDVA) and corrected distance visual acuity (CDVA), reducing corneal aberrations, and improving the regularity of the corneal surface. However, unpredictability of refractive outcome was reported as relatively common with the first-generation topography-guided systems, with many authors recommending topography-guided treatments be approached as a two-stage procedure.]

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Dr. Reinstein and Mr. Archer contributed equally to this work and should be considered as equal first authors.

Prepared in partial fulfillment of the requirements for the doctoral thesis of Mr. Archer for the University of Ulster, Coleraine, Northern Ireland.

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plant.\textsuperscript{1,15} We have shown that the reduced effectiveness of topography-guided treatments in irregularly irregular astigmatism is due to epithelial thickness remodeling, which masks the stromal surface irregularity from front surface topography.\textsuperscript{18-20} The magnitude of the epithelial masking effect is driven by the stromal surface curvature gradient, which is higher in irregularly irregular astigmatism where the irregularities are more localized, hence increasing the stromal curvature gradient.\textsuperscript{21,22} Therefore, our protocol is to first use transepithelial phototherapeutic keratectomy (PTK) in such cases and use topography-guided ablation for regularly irregular astigmatism where the majority of the irregularity can be proved to be on the topography by measuring the epithelial thickness profile.

The purpose of the current study was to evaluate the effectiveness of using topography-guided custom ablation with the MEL 80 and CRS-Master platform to treat regularly irregular astigmatism in the form of decentration or small optical zones after primary myopic laser refractive surgery.

**PATIENTS AND METHODS**

This was a retrospective study of consecutive eyes for patients reporting quality of vision symptoms (including glare, halos, starbursts, and ghosting) related to either a topographic decentration or small optical zone following a primary myopic laser refractive surgery performed at London Vision Clinic, London, United Kingdom, who subsequently underwent a topography-guided re-treatment between November 2005 and August 2013. All primary procedures were performed by one of two experienced surgeons (DZR and GIC) using the MEL 80 excimer laser and VisuMax femtosecond laser (both Carl Zeiss Meditec AG) or zero compression Hansatome microkeratome (Bausch & Lomb, Rochester, NY). During the primary procedure, both the flap and corneal ablation were centered on the coaxially sighted corneal light reflex (CSCLR),\textsuperscript{23} used as the best approximation of the intersection of the visual axis with the cornea.\textsuperscript{24}

A full ophthalmologic examination was performed before re-treatment by an in-house optometrist, as has been described previously.\textsuperscript{25} Manifest refraction was performed using a standardized and validated protocol.\textsuperscript{26} The manifest refraction was repeated by the surgeon at least 1 day before the re-treatment, which was used for treatment planning. Informed consent and permission to use their data for general analysis and publication was obtained from each patient prior to surgery as part of our routine protocol. Because this was a retrospective study, institutional review board approval was not required.

**ATLAS TOPOGRAPHY ACQUISITION**

The ATLAS is a Placido-based topographer with well-documented surface reconstruction accuracy.\textsuperscript{27,28} Multiple ATLAS examinations were obtained for each eye, using artificial tears if the mire rings were irregular. The criteria for selecting the examination to use for treatment were for the examination to be in focus, have smooth, regular mires rings, have continuous data within sufficient diameter, and be repeatable across multiple examinations. The ATLAS topographic examination to be used for treatment was selected by the surgeon.

**CRS-MASTER TOSCA II ABLATION SOFTWARE**

As described previously,\textsuperscript{1} the CRS-Master features an approach for the control of sphere and cylinder (lower order aberrations) while simultaneously correcting topographic irregularities (higher order aberrations). The algorithm uses the corneal elevation and wavefront data to derive the ablation profile. The user can choose to address only the corneal irregularity, leaving corneal sphere and cylinder unchanged (setting “Topography Smooth”), or to perform a treatment that addresses corneal irregularity and calculates the ideal final surface based on the differences between the residual corneal lower order aberrations and the aberration-free manifest refractive error. TOSCA II treatments with the CRS-Master also include radially based ablation depth energy correction algorithms. The TOSCA II algorithm is designed to correct corneal irregularities, control refraction to a specified target, and reduce the induction of higher order aberrations while correcting residual refractive error.

**TREATMENT PLANNING AND ABLATION PROFILE GENERATION**

The CRS-Master software platform (version 2.1) was used to generate the ablation profiles. The ATLAS topographic data were imported into the CRS-Master. The CRS-Master automatically selects the center of the pupil as found by the ATLAS to use as the center for the ablation generation algorithms. The CRS-Master also allows the surgeon to shift this location, and the corneal vertex was chosen for all eyes in this study to match the intended centration to the CSCLR intraoperatively. The corneal vertex was determined as the center of the topography mires as calculated automatically by the ATLAS.

Before lifting the flap in LASIK or before initiating alcohol loosening of the epithelium (in photorefractive keratectomy [PRK]), the pupil-based eye tracker is locked onto the first Purkinje reflex of the coaxially fixating eye following a protocol to account for parallax error. First, the surgeon closes the same eye as the patient’s eye being treated and adjusts the position of the red laser aiming...
beam to be superimposed over the first Purkinje reflex of the cornea while the patient is looking at the green flashing fixation light. The surgeon then switches eyes to now be viewing the patient’s eye with his or her opposite eye. The red laser aiming beam will then appear to be nasal to the fixation light reflex. The surgeon adjusts the aiming beam temporally by eight clicks using the aiming beam horizontal adjustment button (equivalent to 200 μm on the corneal surface). Finally, the surgeon double checks that the centration is perfect by alternately closing his or her right and left eyes; the aiming beam should appear to straddle the Purkinje reflex of the green fixation light when switching between eyes.23

Artemis very high-frequency (VHF) digital ultrasound (ArcScan, Inc., Golden, CO) three-dimensional layered corneal pachymetry29,30 was used to determine whether the treatment could be performed as LASIK. Safety was assessed by checking that the predicted residual stromal thickness after the re-treatment was greater than 250 μm at the location of the maximum ablation (non-central due to the custom profile) and the location of the minimum residual stromal thickness by VHF digital ultrasound.

The parameters that were adjusted to control the ablation depth included manifest refraction, optical zone size, and whether to treat under an existing flap or as a surface procedure. The optical zone size was set as large as possible according to residual stromal thickness safety limits. The transition zone provided a total ablation zone that was 2 mm larger in diameter than the fully corrected optical zone. In cases where manifest refraction was near emmetropia, the “Topography Smooth” algorithm was used, which is designed to regularize the corneal topography leaving a target residual toric surface without affecting refraction.

**Postoperative Course and Evaluation**

Patients were instructed to instill tobramycin–dexamethasone (Tobradex; Alcon Laboratories, Inc., Fort Worth, TX) and ofloxacin (Exocin; Allergan Ltd., Dublin, Ireland) four times daily (our standard protocol for broad-spectrum prophylaxis) and wear plastic shields for sleeping during the first week. Patients were reviewed at 1 day postoperatively by the surgeon, at which point, if any microfolds were identified, flap adjustments were performed at the slit-lamp using a surgical spear under topical anesthetic and antibiotic cover. To ensure any epithelial defects were fully healed, follow-up was continued by the treating surgeon over the early postoperative period. All other follow-up appointments were conducted by the assigned in-house optometrist at 1, 3, and 12 months. UDVA and spherical refraction were obtained at the 1-day postoperative visit. All subsequent follow-up visits included measurements of monocular and binocular UDVA, manifest refraction, and CDVA. Best-corrected mesopic contrast sensitivity was performed at the 3- and 12-month visits. ATLAS corneal topography was performed at 3 and 12 months. Subjective night vision disturbances were discussed with the patient at each visit.

**Visual and Refractive Outcomes Analysis**

Outcome analysis was performed according to the Standard Graphs for Reporting Refractive Surgery.31 Eyes where the intended postoperative refraction was not emmetropia were excluded in the efficacy analysis. Vector analysis was performed as described by Alpins.32 Data from the 1-year visit were used for analysis if available, otherwise 3-month data were used. Subjective symptoms were evaluated based on the notes entered in the medical record using four categories: worse, no change, improved to mild remaining, and resolved.

**Topographic Outcome Analysis**

Topographic analysis of optical zone centration and diameter was performed as described previously.33,34 The preoperative and 3-month postoperative ATLAS axial curvature maps with automatic scaling using expanded colors were imported into Microsoft PowerPoint 2010 (Microsoft Corporation, Redmond, WA). A previously prepared grid and set of concentric circles was overlaid; the lines of the grid were distributed equally with 0.1-mm steps and the concentric circles had radii increasing in 0.2-mm steps, between 4- and 7-mm radii. The map was enlarged on the screen so that the center of the optical zone could be confidently visualized within half a step. The concentric circles were used to visually align and superimpose the best-fitting circle to the optical zone, defined as the region of consistent power. The achieved optical zone diameter was measured to the nearest 0.2 mm using the concentric circles. A histogram of the optical zone diameter before and after re-treatment was generated.

The central grid was then used to determine the centration offset of the optical zone with reference to the corneal vertex, with the optical zone center represented by the (0,0) coordinate of the central grid and the corneal vertex represented by the center of the topography map. The x- and y-coordinates of the location of the optical zone center with reference to the corneal vertex were measured to the nearest 0.05 mm using the central grid.

The x-coordinates obtained for left eyes were mirrored in the vertical axis so that nasal/temporal characteristics of right and left eyes could be combined. The locations of the center of the optical zones, relative...
to the corneal vertex (plotted as the origin), were displayed by plotting the x- and y-coordinates on a 360° polar plot for before and after the re-treatment. The vectorial mean and standard deviation ellipse were calculated for each population using principal component analysis to find the orientation with the greatest standard deviation.

**Corneal Aberrations**

Corneal aberrations obtained by the ATLAS were analyzed in a 6-mm zone using Optical Society of America notation. The change in corneal aberrations was calculated as the difference from before to 3 months after surgery for each third and fourth order Zernike coefficient. The root mean square was also calculated for coma and total third and fourth order higher order aberrations. The change in aberrations was evaluated as a histogram.

**Statistical Analysis**

Student’s t tests were used to calculate the statistical significance of changes in each parameter measured. Microsoft Excel 2010 software (Microsoft Corporation) was used for data entry and statistical analysis. A P value of less than .05 was defined as statistically significant.

**RESULTS**

A total of 75 eyes of 41 patients underwent a topography-guided re-treatment during the study period; 12-month data were available in 66 eyes (88%), with 3-month data in the remaining 9 eyes (12%). Table 1 presents demographic data for before and after the primary myopic procedure and after the topography-guided re-treatment. Table 2 presents information related to the type of procedure performed for the primary treatment and re-treatment. A new LASIK flap was created in 8% (n = 6) of eyes to create a thinner flap to enable the procedure to be performed as LASIK. A side cut only was created in 3% (n = 2) to avoid an area of old epithelial ingrowth.\textsuperscript{35}

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**Table 1**

Demographic Data for Before and After the Primary Myopic Procedure and Topography-guided Re-treatment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes (patients)</td>
<td>73 (40)</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>63%/37%</td>
</tr>
<tr>
<td>Age (y)</td>
<td>35 ± 8 (22 to 57)</td>
</tr>
<tr>
<td>Scotopic pupil (mm)</td>
<td>6.44 ± 0.79 (4.52 to 8.02)</td>
</tr>
<tr>
<td>Primary myopic procedure</td>
<td></td>
</tr>
<tr>
<td>SEQ treated (D)</td>
<td>-7.37 ± 2.17 (-3.49 to -12.47)</td>
</tr>
<tr>
<td>Cyl treated (D)</td>
<td>-0.97 ± 0.89 (0.00 to -4.25)</td>
</tr>
<tr>
<td>Postop SEQ relative to intended target (D)</td>
<td>-0.20 ± 1.02 (-2.88 to +2.42)</td>
</tr>
<tr>
<td>Postop cyl (D)</td>
<td>-0.52 ± 0.37 (0.00 to -1.50)</td>
</tr>
<tr>
<td>Postop UDVA 20/20 or better</td>
<td>60%</td>
</tr>
<tr>
<td>Postop UDVA 20/40 or better</td>
<td>91%</td>
</tr>
<tr>
<td>Loss 1 line CDVA</td>
<td>5.5%</td>
</tr>
<tr>
<td>Loss 2 lines CDVA</td>
<td>1.4%\textsuperscript{b}</td>
</tr>
</tbody>
</table>

**Table 2**

Information Related to the Primary Myopic Procedure and Topography-guided Re-treatment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary myopic procedure</td>
<td></td>
</tr>
<tr>
<td>VisuMax LASIK (80 to 130 (\mu\text{m}) flaps)</td>
<td>49%</td>
</tr>
<tr>
<td>Hansatome microkeratome (160 (\mu\text{m}) flaps)</td>
<td>33%</td>
</tr>
<tr>
<td>Photorefractive keratectomy</td>
<td>18%</td>
</tr>
<tr>
<td>Programmed optical zone diameter (mm), mean ± SD</td>
<td>6.05 ± 0.20 (5.75 to 6.5)</td>
</tr>
</tbody>
</table>

**Topography-guided re-treatment**

| LASIK flap lift                    | 75%                 |
| New VisuMax LASIK flap             | 8%                  |
| Side cut only                      | 3%                  |
| Photorefractive keratectomy        | 14%                 |
| Programmed optical zone diameter (mm), mean ± SD | 6.77 ± 0.38 (5.7 to 7) |

SD = standard deviation

The VisuMax laser is manufactured by Carl Zeiss Meditec, Jena, Germany, and the Hansatome microkeratome is manufactured by Bausch & Lomb, Rochester, NY.
Figure 1. Nine standard graphs for reporting refractive surgery showing the visual and refractive outcomes for 73 eyes after a topography-guided re-treatment to correct a decentration or small optical zone. UDVA = uncorrected distance visual acuity; CDVA = corrected distance visual acuity; D = diopters; postop = postoperative; preop = preoperative; SEQ = spherical equivalent refraction; TIA = target induced astigmatism vector; SIA = surgically induced astigmatism vector.
VISUAL AND REFRACTIVE OUTCOMES

Figure 1 presents the standard graphs for reporting refractive surgery after the topography-guided re-treatment. There were 3 eyes where the refractive correction was more than 1.50 D from the intended target. The primary procedure in all 3 cases had been PRK for very high myopia of -12 to -13 D. No eyes lost more than one line of CDVA.

Figure 2 shows the vector analysis for refractive cylinder after the topography-guided re-treatment. There was a tendency for an overcorrection of refractive cylinder correction as shown in the target induced astigmatism vector versus surgically induced astigmatism vector scatterplot and the correction index polar plot. The angle of error demonstrated an accurate alignment of the treatment; the one case where angle of error was -88° (indicating an increase in cylinder at the same axis) was for an eye with -0.25 diopters cylinder before surgery, increasing to -0.50 diopters cylinder.

Table 3 shows the normalized mesopic contrast sensitivity data for before and after the primary treatment and after the topography-guided re-treatment. There had only been a small drop in contrast sensitivity at 3 cycles per degree (cpd) after the primary treatment, with no change at 6, 12, or 18 cpd. There was a small but statistically significant increase in contrast sensitivity at 6 cpd and no change at 3, 12, or 18 cpd following the topography-guided re-treatment. Patient subjective night vision disturbances were resolved in 55%, improved (mild remaining) in 38%, unchanged in 7%, and worse in 0%.

OPTICAL ZONE CENTRATION

Figure A (available in the online version of this article) shows axial topography maps before and after the topography-guided re-treatment for 5 randomly selected cases. Figure B (available in the online version of this article) shows the 360° polar plot for the center of the optical zone for before and after the re-treatment, which showed a significant improvement in centration (P < .001). Table 4 includes the data for the centration offset of the optical zone relative to the corneal vertex before and after the re-treatment.

OPTICAL ZONE DIAMETER

Table 4 includes the data and Figure 3 shows box plots for the optical zone diameter before and after the topography-guided re-treatment, which showed a significant increase in optical zone diameter (P < .001).

CORNEAL ABERRATIONS

Table 5 reports the change for coma, spherical aberration and total higher order root mean square before and after the topography-guided re-treatment. There was a significant reduction in each of coma, spherical aberration, and higher order root mean square (P < .001).
The current study found the CRS-Master topography-guided custom ablation profile to be effective for optical zone enlargement and recentration following previous myopic corneal laser refractive surgery; optical zone centration was improved by 63% and optical zone diameter was increased by 11% on average. This improvement in topographic optical zone consequently achieved a significant reduction in higher order aberrations, with a 53% reduction in coma and 44% reduction in spherical aberration.

These improvements were associated with a significant improvement in subjective night vision disturbances, with 93% of patients reporting an improvement and 55% reporting complete resolution of symptoms. There was no change in subjective symptoms for 5 eyes (7%) of 3 patients, although there was an obvious topographic improvement in 4 of these eyes, in terms of both centration and optical zone diameter. Such cases of objective but no subjective improvements have been

**DISCUSSION**

The current study found the CRS-Master topography-guided custom ablation profile to be effective for optical zone enlargement and recentration following previous myopic corneal laser refractive surgery; optical zone centration was improved by 63% and optical zone diameter was increased by 11% on average. This improvement in topographic optical zone consequently achieved a significant reduction in higher order aberrations, with a 53% reduction in coma and 44% reduction in spherical aberration.

These improvements were associated with a significant improvement in subjective night vision disturbances, with 93% of patients reporting an improvement and 55% reporting complete resolution of symptoms. There was no change in subjective symptoms for 5 eyes (7%) of 3 patients, although there was an obvious topographic improvement in 4 of these eyes, in terms of both centration and optical zone diameter. Such cases of objective but no subjective improvements have been
reported in other studies. A weakness of this study is that this symptom analysis was based on patient discussion rather than a formal structured questionnaire. There was also no other objective measure of night vision disturbances, except for contrast sensitivity, which showed a slight improvement only at 6 cpd. However, this small change in contrast sensitivity was explained by the fact that there had been no drop in contrast sensitivity after the primary procedure other than a small decrease at 3 cpd. Therefore, an increase in contrast sensitivity might not be expected and patient symptoms were rather related to night vision, such as glare, halo, starburst, and ghosting.

At the same time as addressing the quality of vision symptoms, the uncorrected vision and refractive outcomes also demonstrated a significant improvement, with UDVA of 20/20 or better improving from 60% to 80% of eyes. All eyes achieved 20/32 or better after topography-guided re-treatment compared with 82% before. Safety was also excellent with no eyes losing two lines of CDVA, and 27% gaining one line. Aside from the 3 eyes with previous high myopic PRK, refractive predictability was good given that most treatments were for less than ±1.00 D and the main aim of treatment being topographic regularization. There was a tendency for both myopic and hyperopic treatments to end up slightly myopic; mean postoperative spherical equivalent refraction was -0.20 D.

To consider these results in the context of other topography-guided systems, a literature search was performed to identify published studies reporting outcomes of topography-guided re-treatment for decentration and/or optical zone enlargement. Studies that reported only treatment of irregularly irregular astigmatism (eg, after previous corneal transplant) and treatment of keratoconus were excluded. For studies that included both regularly and irregularly irregular astigmatism, only the cases with regularly irregular astigmatism were considered where possible (either by having been analyzed as a separate group or extracting data for those cases if all patient data were available). Sixteen studies were identified and included for analysis. All studies reported improvement or resolution of quality of vision symptoms in the majority of patients, demonstrating the effectiveness of topography-guided treatment of regularly irregular astigmatism.

Table A (available in the online version of this article) provides a summary of the visual and refractive outcomes for these studies. Refractive predictability has improved over time, with the modern systems achieving significantly better refractive control than the first-generation systems. Safety was consistently good, with a loss of two lines of CDVA in only 4 eyes across all studies (0.73%).

Table B (available in the online version of this article) provides a summary of corneal aberration change for those studies where this data were reported. All studies showed a significant reduction in corneal aberrations. Topographic decentration was measured in only three studies, as summarized in Table C (available in the online version of this article), and topographic optical zone diameter was reported in only one study, as summarized in Table D (available in the online version of this article). In both cases, a significant improvement was achieved by topography-guided re-treatment.

As described earlier, epithelial remodeling has been identified as a limiting factor for conventional topography-guided treatment based on front surface corneal topography data. Chen et al. pioneered the technique of combining transepithelial PTK with topography-guided treatment into a single treatment, such that the transepithelial PTK treatment was performed in the epithelium, allowing for a more rapid and controlled remodeling of the corneal surface.

### Table 5

**Corneal Aberrations in a 6-mm Analysis Zone Before and After Topography-guided Re-treatment**

<table>
<thead>
<tr>
<th>Corneal Aberrations (µm)</th>
<th>Coma</th>
<th>Spherical Aberration</th>
<th>HORMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>After primary treatment</td>
<td>0.60 ± 0.35 (0.01 to 1.73)</td>
<td>0.69 ± 0.21 (0.33 to 1.33)</td>
<td>0.97 ± 0.34 (0.50 to 1.95)</td>
</tr>
<tr>
<td>After topography-guided re-treatment</td>
<td>0.28 ± 0.17 (0.02 to 0.79)</td>
<td>0.38 ± 0.24 (-0.01 to 1.12)</td>
<td>0.59 ± 0.23 (0.24 to 1.39)</td>
</tr>
<tr>
<td>Change</td>
<td>-0.32 ± 0.35 (-1.29 to 0.29)</td>
<td>-0.30 ± 0.23 (-0.88 to 0.39)</td>
<td>-0.39 ± 0.32 (-1.16 to 0.15)</td>
</tr>
<tr>
<td>Change (%)</td>
<td>53%&lt;sup&gt;b&lt;/sup&gt;</td>
<td>44%&lt;sup&gt;b&lt;/sup&gt;</td>
<td>39%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>&lt;sup&gt;P&lt;/sup&gt;</td>
<td>&lt; .001</td>
<td>&lt; .001</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Increase in aberrations</td>
<td>21%</td>
<td>10%</td>
<td>11%</td>
</tr>
<tr>
<td>Decrease in aberrations</td>
<td>79%</td>
<td>90%</td>
<td>89%</td>
</tr>
</tbody>
</table>

<sup>HORMS = higher order aberrations root mean square</sup>
<sup>aValues are presented as mean ± standard deviation.</sup>
<sup>bDecrease in aberrations.</sup>
thelial PTK corrects the irregularities masked by the epithelium and the topography-guided treatment corrects the irregularity visible on the front corneal surface. Vinciguerra et al. developed another approach to this problem by planning the treatment based on topography data obtained intraoperatively, having first removed the epithelium. Finally, we previously described the first case in which the epithelial thickness profile was incorporated into the ablation generation algorithm to derive a stromal topography-guided ablation. It is likely that the ideal future of therapeutic refractive surgery will be based on stromal surface shape itself to account for the masking effect of the epithelium.

Wavefront-guided custom ablation is an alternative option for treating highly aberrated eyes, but the reduction in aberrations reported for wavefront-guided treatments has been lower than for topography-guided treatments. Another disadvantage of wavefront-guided treatments is that these are forced to be centered on the entrance pupil because this is where the data are captured. These treatments are therefore less effective for recenteration of the optical zone to the corneal vertex, and can actually increase the decentration in eyes with a large angle kappa.

The topography-guided algorithm described in the current study is part of the CRS-Master. MEL 80, CRS-Master, and TOSCA II re-treatments appear effective for correcting topographic decentrations, optical zone enlargement, and reduction of higher order aberrations following unsatisfactory outcomes of previous refractive surgery with good simultaneous control of refractive error.

**AUTHOR CONTRIBUTIONS**

Study concept and design (DZR, GIC, TJA); data collection (DZR, GIC, TJA, AS, ELR); analysis and interpretation of data (DZR, GIC, TJA, AS, ELR, AN, TM); writing the manuscript (DZR, TJA, AS); critical revision of the manuscript (GIC, ELR, AN, TM); statistical expertise (DZR, TJA); obtaining funding (DZR); supervision (AN, TM)

**REFERENCES**

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Figure A. Four example cases showing the axial curvature map before and after a topography-guided re-treatment. The difference map is shown in the third column, next to the ablation profile that was used; the region of flattening on the difference map corresponded with the area of maximum ablation.
Figure B. Plot showing the optical zone center relative to the corneal vertex (A) before and (B) after the primary myopic treatment. The red data point indicates the vector mean and the red oval indicates the standard deviation (SD) ellipse.
<table>
<thead>
<tr>
<th>Study</th>
<th>Eyes</th>
<th>Patient Type</th>
<th>Software / Laser</th>
<th>Pre</th>
<th>Post</th>
<th>± 0.50</th>
<th>± 1.00</th>
<th>Pre</th>
<th>Post</th>
<th>Pre</th>
<th>Post</th>
<th>Pre</th>
<th>Post</th>
<th>Efficacy</th>
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<tr>
<td>Knorz &amp; Jendritza, 2000⑵</td>
<td>11</td>
<td>Decentration, small zone</td>
<td>CAS / 117C</td>
<td>-1.00 ± 2.24 (-3.63 to +3.50)</td>
<td>+0.20 ± 2.41 (-4.00 to +3.70)</td>
<td>NR</td>
<td>NR</td>
<td>0.48</td>
<td>0.40</td>
<td>0.40</td>
<td>0.24</td>
<td>NR</td>
<td>NR</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>Alessio et al., 2001⑸</td>
<td>32</td>
<td>Decentration</td>
<td>CIPTA / LaserScan 2000</td>
<td>-2.62 ± 1.90 (-6.75 to -0.75)</td>
<td>-0.05 ± 0.70 (-1.50 to +1.00)</td>
<td>69%</td>
<td>88%</td>
<td>0.83</td>
<td>0.13</td>
<td>0.13</td>
<td>0.04</td>
<td>NR</td>
<td>59%</td>
<td>91%</td>
<td>0%</td>
</tr>
<tr>
<td>Alò et al., 2003⑶</td>
<td>26</td>
<td>Regularly irregular astigmatism</td>
<td>TOPOLINK / 217C</td>
<td>-1.10 ± 2.00 (-6.00 to +2.00)</td>
<td>-0.30 ± 0.84 (-3.00 to +1.00)</td>
<td>69%</td>
<td>89%</td>
<td>NR</td>
<td>0.20</td>
<td>0.16</td>
<td>0.09</td>
<td>NR</td>
<td>0%</td>
<td>96%</td>
<td>0%</td>
</tr>
<tr>
<td>Kymionis et al., 2004⑷</td>
<td>11</td>
<td>Decentration</td>
<td>TOSCA / MEL 70</td>
<td>-0.14 ± 1.98 (-1.75 to +3.00)</td>
<td>+0.46 ± 1.02 (-1.00 to +1.75)</td>
<td>NR</td>
<td>NR</td>
<td>0.35</td>
<td>0.12</td>
<td>0.13</td>
<td>0.02</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0%</td>
</tr>
<tr>
<td>Lin &amp; Mandle, 2004⑴</td>
<td>8*</td>
<td>Decentration</td>
<td>C-CAP / 54</td>
<td>0.20 ± 1.78 (-1.75 to +4.13)</td>
<td>+0.77 ± 1.27 (-0.90 to +3.63)</td>
<td>50%</td>
<td>75%</td>
<td>0.32</td>
<td>0.29</td>
<td>0.14</td>
<td>0.10</td>
<td>38%</td>
<td>25%</td>
<td>79%</td>
<td>0%</td>
</tr>
<tr>
<td>Kanellopoulos, 2005⑩</td>
<td>27</td>
<td>Decentration, small zone, and other</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>-1.12 ± 1.59 (-3.88 to +0.25)</td>
<td>-0.88 ± 0.94 (-2.38 to +0.75)</td>
<td>NR</td>
<td>NR</td>
<td>0.39</td>
<td>0.10</td>
<td>0.20</td>
<td>0.02</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0%</td>
</tr>
<tr>
<td>Janiov et al., 2008⑩</td>
<td>16</td>
<td>Decentration, small zone, and other</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>-2.16 ± 3.07 (-7.88 to +2.25)</td>
<td>-0.97 ± 0.94 (-2.25 to +0.50)</td>
<td>NR</td>
<td>NR</td>
<td>0.81</td>
<td>0.29</td>
<td>0.07</td>
<td>0.05</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0%</td>
</tr>
<tr>
<td>Tada et al., 2007⑧</td>
<td>32</td>
<td>Decentration, small zone, asymmetric astigmatism</td>
<td>NAVEX / EC-5000</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>59%</td>
<td>33%</td>
</tr>
<tr>
<td>Wu et al., 2008⑧</td>
<td>18</td>
<td>Decentration</td>
<td>AstraPro2.2t / LaserScan LSX</td>
<td>-1.87 ± 1.38</td>
<td>-0.13 ± 0.57</td>
<td>67%</td>
<td>89%</td>
<td>0.43</td>
<td>0.03</td>
<td>0.08</td>
<td>0.01</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Lin et al., 2008⑨①</td>
<td>67</td>
<td>Decentration</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>NR</td>
<td>NR</td>
<td>76%</td>
<td>94%</td>
<td>0.41</td>
<td>0.08</td>
<td>0.11</td>
<td>0.00</td>
<td>NR</td>
<td>76%</td>
<td>94%</td>
<td>0%</td>
</tr>
<tr>
<td>Lin et al., 2008⑤①</td>
<td>48</td>
<td>Small zone</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>NR</td>
<td>NR</td>
<td>81%</td>
<td>94%</td>
<td>0.37</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td>NR</td>
<td>63%</td>
<td>94%</td>
<td>0%</td>
</tr>
<tr>
<td>Alò et al., 2008⑧②③</td>
<td>34</td>
<td>Decentration</td>
<td>OAM / ESIRIS</td>
<td>+0.47 ± 1.16 (-1.75 to +3.00)</td>
<td>-0.06 ± 0.57 (-1.50 to +1.25)</td>
<td>74%</td>
<td>97%</td>
<td>0.20</td>
<td>0.12</td>
<td>0.07</td>
<td>0.05</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>3%</td>
</tr>
<tr>
<td>Alò et al., 2008⑧③</td>
<td>28</td>
<td>Small zone</td>
<td>OAM / ESIRIS</td>
<td>-0.22 ± 1.14 (-2.13 to +2.50)</td>
<td>+0.33 ± 0.54 (-1.13 to +1.25)</td>
<td>NR</td>
<td>NR</td>
<td>0.33</td>
<td>0.17</td>
<td>0.11</td>
<td>0.08</td>
<td>43%</td>
<td>18%</td>
<td>89%</td>
<td>0%</td>
</tr>
<tr>
<td>Reinstein et al., 2009②</td>
<td>33*</td>
<td>Decentration, small zone</td>
<td>TOSCA II / MEL 80</td>
<td>-0.83 ± 1.25 (-3.25 to +1.13)</td>
<td>+0.02 ± 0.75 (-1.63 to +2.38)</td>
<td>70%</td>
<td>82%</td>
<td>0.15</td>
<td>0.05</td>
<td>-0.03</td>
<td>-0.05</td>
<td>88%</td>
<td>68%</td>
<td>88%</td>
<td>0%</td>
</tr>
<tr>
<td>Lin et al., 2012③①</td>
<td>37</td>
<td>Decentration</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>NR</td>
<td>NR</td>
<td>76%</td>
<td>94%</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>74%</td>
<td>92%</td>
</tr>
<tr>
<td>Lin et al., 2012③②</td>
<td>25</td>
<td>Small zone</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>NR</td>
<td>NR</td>
<td>81%</td>
<td>92%</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>62%</td>
<td>88%</td>
</tr>
<tr>
<td>Aslanides et al., 2012③④</td>
<td>18</td>
<td>Symptomatic</td>
<td>OAM / ESIRIS</td>
<td>-0.38 ± 1.85 (-2.75 to +3.75)</td>
<td>-0.09 ± 0.22 (-0.50 to +0.25)</td>
<td>90%</td>
<td>100%</td>
<td>0.32</td>
<td>0.03</td>
<td>0.05</td>
<td>0.00</td>
<td>55%</td>
<td>73%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Allan &amp; Hassan, 2013⑦①</td>
<td>5*</td>
<td>Irregular astigmatism</td>
<td>ZOAD / Pulsar Z1</td>
<td>-0.15 ± 1.10 (-2.00 to +0.75)</td>
<td>+0.83 ± 0.92 (-0.13 to +1.88)</td>
<td>40%</td>
<td>60%</td>
<td>0.46</td>
<td>0.11</td>
<td>0.05</td>
<td>-0.07</td>
<td>60%</td>
<td>40%</td>
<td>80%</td>
<td>0%</td>
</tr>
<tr>
<td>Reinstein et al., 2018, (current)</td>
<td>73</td>
<td>Decentration, small zone, and other</td>
<td>TOSCA II / MEL 80</td>
<td>-0.20 ± 1.02 (-2.88 to +2.42)</td>
<td>-0.20 ± 0.63 (-1.88 to +2.25)</td>
<td>71%</td>
<td>90%</td>
<td>-0.05</td>
<td>-0.07</td>
<td>-0.02</td>
<td>0.05</td>
<td>90%</td>
<td>82%</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

SEQ = spherical equivalent refraction; D = diopters; UDVA = uncorrected distance visual acuity; CDVA = corrected distance visual acuity; pre = preoperative; post = postoperative; NR = not reported; C-CAP = contoured ablation pattern; CAM = Custom Ablation Manager
* Results calculated from data reported for regularly-irregular astigmatism cases only.

The CAS is manufactured by EagleSys Premic; Irvine, CA; TOPOLINK / 117C is manufactured by Bausch & Lomb, Salt Lake City, UT; CIPTA is manufactured by LGL, Ivano, Italy; LaserScan 2000, LaserScan LSX is manufactured by Lasermight, Orlando, FL; TOSCA / MEL 80 is manufactured by Carl Zeiss Meditec, Jena, Germany; SA is manufactured by Johnson & Johnson, New Brunswick, NJ; Topolyzer / ALLEGRETTO WAVE is manufactured by Alcon Laboratories, Inc., Fort Worth, TX; ESIRIS is manufactured by SCHMIND eye-tech-solutions, Reinstein, Germany; ZOAD / Pulsar Z1 platform NeoYAG ablative laser is manufactured by CV Laser Pty Ltd., Osborne Park, Australia.
<table>
<thead>
<tr>
<th>Study</th>
<th>Eyes</th>
<th>Software / Laser</th>
<th>Pre</th>
<th>Post</th>
<th>Pre</th>
<th>Post</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kymionis et al., 2004³</td>
<td>11</td>
<td>TOSCA / MEL 70</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0.61</td>
<td>0.37</td>
</tr>
<tr>
<td>Lin &amp; Manche, 2004¹¹</td>
<td>8*</td>
<td>C-CAP / S4</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0.66</td>
<td>0.36</td>
</tr>
<tr>
<td>Toda et al., 2007⁸</td>
<td>32</td>
<td>NAVEX / EC-5000</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>1.38</td>
<td>1.01</td>
</tr>
<tr>
<td>Wu et al., 2008⁷</td>
<td>18</td>
<td>AstraPro2.2z / LaserScan LSX</td>
<td>1.33</td>
<td>0.99</td>
<td>1.36</td>
<td>1.02</td>
<td>1.89</td>
<td>1.50</td>
</tr>
<tr>
<td>Alió et al., 2008³⁵</td>
<td>34</td>
<td>CAM / ESIRIS</td>
<td>0.88</td>
<td>0.61</td>
<td>0.02</td>
<td>-0.19</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Alió et al., 2008¹⁷</td>
<td>28</td>
<td>CAM / ESIRIS</td>
<td>0.61</td>
<td>0.43</td>
<td>0.75</td>
<td>0.43</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Reinstein et al., 2009¹¹</td>
<td>33*</td>
<td>TOSCA II / MEL 80</td>
<td>0.25</td>
<td>0.30</td>
<td>0.56</td>
<td>0.24</td>
<td>0.68</td>
<td>0.54</td>
</tr>
<tr>
<td>Aslanides et al., 2012³⁵⁷</td>
<td>18</td>
<td>CAM / ESIRIS</td>
<td>0.45</td>
<td>0.25</td>
<td>0.22</td>
<td>0.10</td>
<td>0.75</td>
<td>0.45</td>
</tr>
<tr>
<td>Reinstein et al., 2018 (current)</td>
<td>73</td>
<td>TOSCA II / MEL 80</td>
<td>0.60</td>
<td>0.28</td>
<td>0.69</td>
<td>0.38</td>
<td>0.97</td>
<td>0.59</td>
</tr>
</tbody>
</table>

HORMS = higher order aberrations root mean square; pre = preoperative; post = postoperative; NR = not reported; C-CAP = custom-contoured ablation pattern; CAM = Custom Ablation Manager. The TOSCA / MEL 70 and MEL 80 are manufactured by Carl Zeiss Meditec, Jena, Germany; S4 is manufactured by Johnson & Johnson, New Brunswick, NJ; LaserScan LSX is manufactured by Lasersight, Orlando, FL; and ESIRIS is manufactured by SCHWIND eye-tech-solutions, Kleinostheim, Germany.
### TABLE C

<table>
<thead>
<tr>
<th>Study</th>
<th>Eyes</th>
<th>Software / Laser</th>
<th>Optical Zone Diameter (mm)</th>
<th>Pre</th>
<th>Post</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lin et al., 2012</td>
<td>25</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td></td>
<td>3.50</td>
<td>5.20</td>
<td>1.70 (49%)</td>
</tr>
<tr>
<td>Reinstein et al., 2018</td>
<td>73</td>
<td>TOSCA II / MEL 80</td>
<td></td>
<td>5.65 ± 0.52 (4.80 to 7.00)</td>
<td>6.32 ± 0.52 (5.00 to 7.60)</td>
<td>0.67 (11%)</td>
</tr>
</tbody>
</table>

*pre = preoperative; post = postoperative

The Topolyzer/ALLEGRETTO WAVE is manufactured by Alcon Laboratories, Inc., Fort Worth, TX, and the TOSCA II, MEL 80 is manufactured by Carl Zeiss Meditec, Jena, Germany.

### TABLE D

<table>
<thead>
<tr>
<th>Study</th>
<th>Eyes</th>
<th>Software / Laser</th>
<th>Optical Zone Centration (mm)</th>
<th>Pre</th>
<th>Post</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wu et al., 2008</td>
<td>18</td>
<td>AstraPro2.2z / LaserScan LSX</td>
<td>1.32 ± 0.28 (0.82 to 1.90)</td>
<td>0.61 ± 0.23 (0.25 to 1.06)</td>
<td>-0.71 (54%)</td>
<td></td>
</tr>
<tr>
<td>Lin et al., 2008</td>
<td>67</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>0.92</td>
<td>0.30</td>
<td>-0.62 (67%)</td>
<td></td>
</tr>
<tr>
<td>Lin et al., 2012</td>
<td>37</td>
<td>Topolyzer / ALLEGRETTO WAVE</td>
<td>1.10</td>
<td>0.40</td>
<td>-0.70 (64%)</td>
<td></td>
</tr>
<tr>
<td>Reinstein et al., 2018</td>
<td>73</td>
<td>TOSCA II / MEL 80</td>
<td>0.58 ± 0.26 (0.05 to 1.28)</td>
<td>0.21 ± 0.14 (0.00 to 0.54)</td>
<td>-0.37 (64%)</td>
<td></td>
</tr>
</tbody>
</table>

*pre = preoperative; post = postoperative

The AstraPro2.2z/LaserScan LSX is manufactured by Lasersight, Orlando, FL; the Topolyzer/ALLEGRETTO WAVE is manufactured by Alcon Laboratories, Inc., Fort Worth, TX; and the TOSCA II/MEL 80 is manufactured by Carl Zeiss Meditec, Jena, Germany.