Wavefront Optimized Versus Custom-Q Treatments in Surface Ablation for Myopic Astigmatism With the WaveLight ALLEGRETTO Laser

Aleksandar Stojanovic, MD; Ling Wang, MD, MS; Mirko R. Jankov, MD, PhD; Tore A. Nitter, MD, PhD; Qinmei Wang, MD

ABSTRACT

PURPOSE: To compare treatments with wavefront optimized and custom-Q ablations.

METHODS: Two consecutive groups of eyes were treated for myopia and astigmatism with surface ablation. One group was treated with wavefront optimized ablation and the second group was treated with custom-Q ablation. Preoperative and 3-month postoperative Q-values, higher order aberrations, low contrast visual acuity, and classic outcome parameters were analyzed.

RESULTS: The wavefront optimized ablation group was comprised of 46 eyes of 23 patients with a mean spherical equivalent refraction (SE) of −3.64 diopters (D) (range: −1.15 to −8.25 D); mean Q-value changed from −0.33 preoperatively to 0.06 postoperatively. The custom-Q ablation group was comprised of 42 eyes of 21 patients with a mean SE of −3.24 D (range: −1.47 to −8.00 D); mean Q-value changed from −0.36 preoperatively to −0.03 postoperatively. A statistically significant difference in postoperative change in Q-values (P=.049) between the two groups was noted, but there was no such difference in higher order aberrations, low contrast visual acuity, or classic outcome parameters.

CONCLUSIONS: Custom-Q ablation resulted in a mean postoperative asphericity that was closer to preoperative compared to wavefront optimized ablation, whereas the other outcome parameters showed no statistically significant differences. [*J Refract Surg.* 2008;24:779-789.]

One problem with standard myopic excimer laser treatment is decrease in visual performance manifested by reduction in contrast sensitivity and night vision.[1] It has been reported that these treatments induce an increase in spherical aberration[2] and that such increase was mainly related to change of corneal asphericity.[3,4] The curvature of the anterior surface of an aspheric cornea changes with distance from the apex so that the surface flattens towards the periphery in prolate corneas but steepens towards the periphery in oblate corneas. To describe this change in curvature or asphericity, Q-values are used. A negative Q-value describes a prolate surface, and a positive Q-value describes an oblate surface. The standard (non-aspheric) myopic ablation changes the normal prolate corneal shape in an oblate direction,[5] and this shift seems to be directly correlated with the amount of correction.[6] Modern refractive ablations, with considerations to control asphericity, reduce this oblate shift but typically become progressively less effective towards high degrees of myopia.[5,7,8]

This study compares the WaveLight ALLEGRETTO (WaveLight AG, Erlangen, Germany) wavefront optimized treatment and its custom-Q treatment. The wavefront optimized ablation has an aspheric profile in which the amount of asphericity is not adjustable (and is the default treatment type on that platform). Similarly, the custom-Q ablation is also an aspheric ablation, but it adds the ability for the surgeon to define

From the Eye Department, University Hospital of North Norway and SynsLaser Kirurgi, Tomsø, Norway (Stojanovic); School of Ophthalmology and Optometry and Eye Hospital, Wenzhou Medical College, Wenzhou, Zhejiang, China (L. Wang, Q. Wang); Milos Klinika, Medical Academy – US Medical School, Belgrade, Serbia (Jankov); and Øyelegesenteret, Tomsø, Norway (Nitter).

This study was supported by SynsLaser Kirurgi, Tomsø, Norway.

Dr Jankov is a paid consultant for WaveLight AG, Erlangen, Germany. The remaining authors have no proprietary or financial interest in the materials presented herein.

Correspondence: Aleksandar Stojanovic, MD, Fløyvn 32, 9020 Tromsdalen, Norway. Tel: 47 90693319; Fax: 47 77647929; E-mail: aleks@online.no

Received: February 26, 2007

Accepted: November 7, 2007

Posted online: March 15, 2008

the intended Q-shift (postoperative Q-value minus preoperative Q-value) by specifying a desired asphericity target. Unlike wavefront- or topography-guided custom treatments, which attempt to achieve an ideal optical/corneal surface based on detailed preoperative aberrometry and topography maps, the only preoperative data that custom-Q treatment uses (in addition to refractive data) is a value of the mean corneal asphericity. It does not attempt to achieve a given asphericity at all points within the optical zone because no data on local values in preoperative asphericity are taken into account in programming of the ablation; it aims only to change the mean asphericity by symmetrically adjusting the number of mid-peripheral laser pulses. This study compares the effect of these two types of treatments by evaluating Q-values, higher order aberations, low contrast visual acuity, and classic outcome parameters.

PATIENTS AND METHODS

One hundred eyes of 50 patients seeking laser correction at SynsLaser Clinic in Tromsø, Norway, were enrolled in a retrospective, consecutive case study. Inclusion criteria were age ⩾20 years; no contact lens wear for 2 weeks before baseline examination; manifest refraction spherical equivalent (MRSE) between −1.00 and −10.00 diopters (D) with ⩽−3.50 D of refractive astigmatism; stable refractive error for ⩾2 years; and best spectacle-corrected visual acuity (BSCVA) of 20/25 or better. Exclusion criteria were eye pathology, including keratoconus or keratoconus suspect; corneal thickness <480 µm; previous eye surgery; glaucoma; diabetes; and systemic diseases that could affect corneal wound healing (eg, collagen vascular diseases). Every patient provided an informed consent before being enrolled in the study. The first 50 eyes were treated with WaveLight ALLEGRETTO wavefront optimized ablation, representing one group, and the remaining 50 eyes were treated with custom-Q ablation, representing the second group.

Preoperative examination consisted of slit-lamp microscopy, uncorrected visual acuity (UCVA), manifest refraction and BSCVA (RT 2100 system; NIDEK Co Ltd, Gamagori, Japan), low contrast visual acuity (Optec 3500; Stereo Optical Co Inc, Chicago, Ill), Goldmann applanation tonometry, central ultrasound pachymetry (Corneo-Gage Plus; Sonogage Inc, Cleveland, Ohio), and corneal tomography (Orbscan II; Bausch & Lomb, Rochester, NY). Asphericity values for two orthogonal hemi-meridians covering the apical 30° (a circle with a diameter between 3.8 and 4.4 mm, depending on the corneal curvature) were provided by placido disk–based corneal topography (Allegro Wave Topolyzer, WaveLight AG). These measurements were performed three times for each eye, and the mean was used as a basis for calculation of the preoperative Q-value (done by the laser software) in the custom-Q group. Wavefront analysis was performed at 6-mm pupil diameter with WaveLight Allegro Wave Analyzer. This ray-tracing device uses mathematical analysis of a retinal spot pattern captured by a video camera. The first derivative of the wavefront is calculated from the deviations of spot positions from their ideal position. Wavefront aberrations are expressed in 27 Zernike coefficients up to the 6th order, as proposed by Optical Society of America (OSA) and its Vision Science and Its Applications (VSIA) taskforce.

The laser treatments were performed with the ALLEGRETTO excimer laser. This laser performs at a repetition rate of 400 Hz and produces a Gaussian beam profile with spot size of 0.68 mm (as measured by the full-width, half-maximum [FWHM] method, established by the Alliance for Telecommunication Industry Solutions [ATIS]). An infrared pupillary eye tracker with latency of 6 ms was used. Optical zone diameter of 6.5 mm and transition zone of 1.0 mm were used in all surgeries in both groups.

The target refraction in all eyes was emmetropia. Manifest refraction, adjusted with a modified manufacturer's nomogram, was used as the programming basis of all treatments. Regarding the choice of ablation type, the ALLEGRETTO wavefront optimized ablation was used in the wavefront optimized ablation group, whereas the custom-Q ablation was used in the custom-Q ablation group. The Q-target in the latter group was set to either −0.5 or −0.6, depending on the patient's preoperative asphericity and age. If the preoperative Q-value was between 0 and −0.2, and if the patient's age was <45 years, the Q-target was set to −0.5, whereas in all other cases the Q-target was set to −0.6.

NOMOGRAM ADJUSTMENT FOR CUSTOM-Q TREATMENT

Before the custom-Q ablation was programmed, the central ablation depth for the same refractive treatment was calculated by use of the standard wavefront optimized software. After setting the Q-target in the custom-Q software, the myopic correction component was reduced until the central ablation depth decreased to the level previously computed by the wavefront optimized software. Finally, a 10% increase of the astigmatic component was made.

All surgeries were performed as surface ablation procedures. A specific protocol was used to reduce postoperative pain and haze, by minimizing the inflammation reaction and minimizing the increased sensibility to ultraviolet radiation.[9] A detailed protocol is described in a previous study.[10] In addition, any tendency towards

TABLE 1

Preoperative Demographic and Refractive Data of Patients in the Wavefront Optimized Ablation and Custom-Q Ablation Groups*

Characteristic	Wavefront Optimized Ablation Group	Custom-Q Ablation Group	*P* Value
Age (y)	33.5±8.5 (20 to 52)	34.7±8.3 (20 to 50)	.50
Sex (male/female, %)	69.57/30.43	57.14/42.86	.22
MRSE (D)	−3.64±1.92 (−8.25 to −1.15)	−3.24±1.47 (−8.00 to −1.13)	.27
Cylinder (D)	−0.92±0.80 (0 to −3.25)	−1.03±0.90 (0 to −3.25)	.54
BSCVA (logMar)	20/19	20/19	.36
Asphericity (Q)	−0.33±0.10 (−0.57 to −0.13)	−0.36±0.12 (−0.60 to −0.09)	.21
Total RMS HOAs (μm)	0.20±0.08 (0.10 to 0.51)	0.20±0.06 (0.10 to 0.41)	.43
Spherical aberration (μm)	−0.02±0.06 (−0.22 to 0.11)	−0.01±0.06 (−0.10 to 0.09)	.63
RMS 3rd order HOAs	0.16±0.08 (0.05 to 0.47)	0.18±0.09 (0.06 to 0.54)	.55

MRSE = manifest refraction spherical equivalent, BSCVA = best spectacle-corrected visual acuity, RMS = root-mean-square, HOAs = higher order aberrations
**Values represented as mean±standard deviation (range).*

dry eye that was identified preoperatively was treated with collagen punctal plugs and lubricating gels. Omega-3 fatty acid (1000 mg daily) was used 1 to 2 weeks before surgery and 2 weeks postoperatively. Nonsteroidal anti-inflammatory treatment was started with ibuprofen (Weifa AS, Oslo, Norway) 600 mg four times a day two days before surgery and continued through day 3 postoperatively. Prednisolone 50 mg (Nycomed International Management GmbH, Asker, Norway) and alprazolam 0.5 mg (Xanax; Pfizer Inc, New York, NY) were given orally as single doses 30 minutes before the surgery.

Corneal Marking and Manual Fixation

Corneal marking was used to minimize the initial ablation placement errors. Manual globe fixation (14-mm Thornton fixation ring; Altomed Ltd, Tyne & Wear, England) was used in addition to the eye tracker to avoid decentrations due to a parallax effect that occurs with patient fixation loss during ablation.[11,12] Perilimbal marks at 3 o'clock and 9 o'clock, defining a horizontal line, were placed with the help of a slit lamp, by rotating the slit into the horizontal position. Prior to setting the marks, the patient's head tilt was adjusted so that both pupils were leveled along the same horizontal line. The ablation area and its center were defined by a 9-mm circle as well as by a horizontal (x) and a vertical (y) line. All markings were placed simultaneously by use of a single corneal marker (Gebauer Medizintechnik GmbH, Neuhausen, Germany). All ablations were centered on the corneal vertex, whose position was determined by preoperative corneal topography. Therefore, an offset, representing the coordinates of the vertex relative to the center of the pupil, was programmed into the eye tracker. After the epithelial removal and before the laser ablation, torsional, x, y, and rotational positions of the eye were checked with respect to the peripheral rests of the x and y marking lines and the calibrated projected laser cross. The patient's fixation was then confirmed by identification of the position of the first Purkinje image and the globe fixation ring was gently applied and held during the entire ablation.

Frozen "balanced salt solution (BSS) popsicle" (frozen sterile merocel sponge soaked in BSS) was applied with an Amoils brush (Innovative Excimer Solutions, Toronto, Canada) on the cornea for 15 seconds before epithelium removal, for 5 seconds after deepithelialization, and for 15 seconds after laser ablation.

After the refractive ablation, a short phototherapeutic keratectomy ablation, 5-μm depth and 8-mm diameter, was applied on the wet cornea (hydrated with a thin layer of hyaluronic acid 0.025%) for smoothing purposes.[13] Mitomicyn C 0.02% was applied for 12 seconds if ablation depth exceeded 100 μm, followed by irrigation with 30 mL chilled BSS.

Patients were evaluated on postoperative day 4 to 7 (upon bandage contact lens removal) and 1 and 3 months after surgery. At 1-month follow-up, examination included slit-lamp microscopy, Orbscan tomography, manifest refraction, UCVA, and BSCVA. At 3-month follow-up, examination was identical to preoperative.

Pre- and postoperative parameters as well as the preoperative versus postoperative changes were analyzed using NCSS 2004 (Statistical Systems, Kaysville, Utah) software. Paired *t*-test was used to evaluate the difference

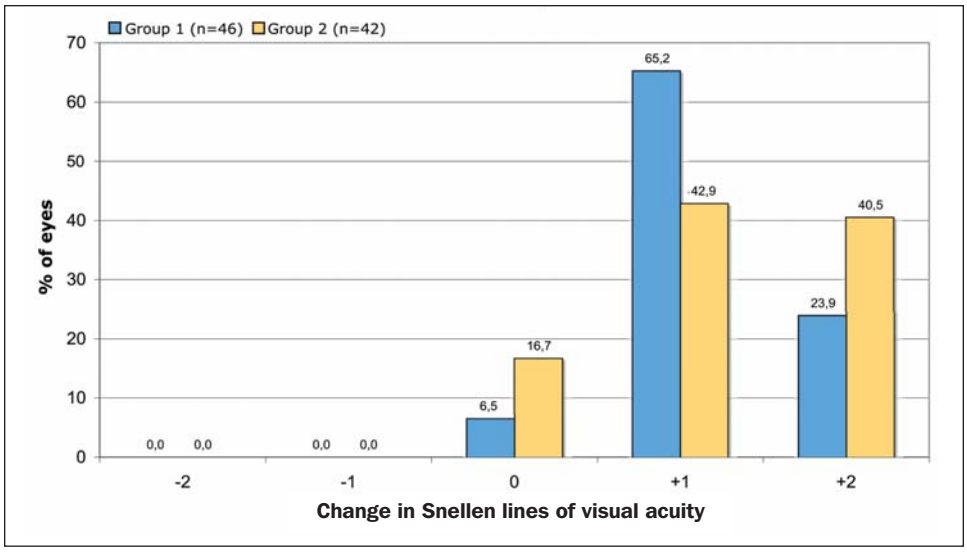

Figure 1. Safety in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2) 3 months after surgery showing the gain/loss of lines of best spectacle-corrected visual acuity.

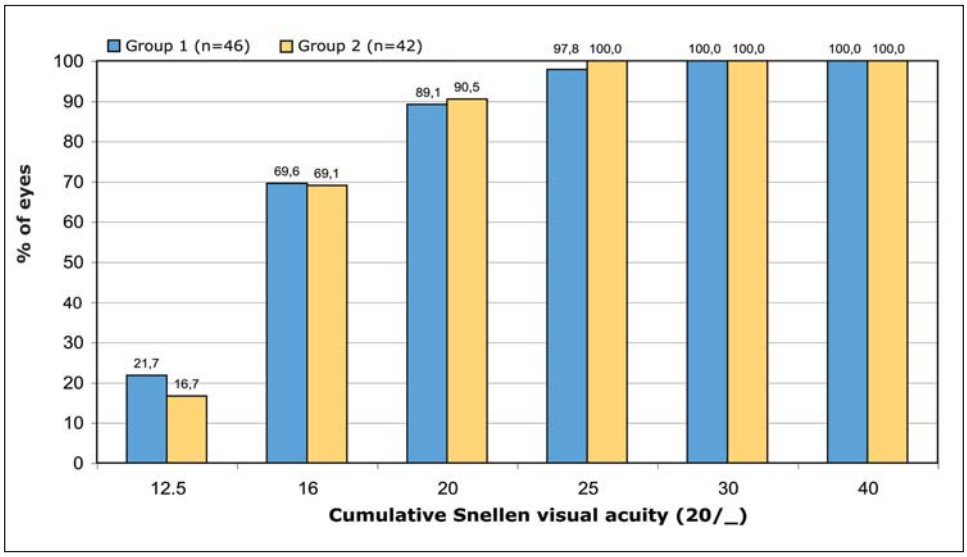

Figure 2. Efficacy in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2) 3 months after surgery showing the cumulative uncorrected visual acuity.

between pre- and postoperative parameters. Two-sample *t* test was used to evaluate the difference between the two groups. A P value $<.05$ was considered statistically significant. Pearson test was used for testing of correlations. Vector analysis was used for calculating the changes between the spherocylinders before and after surgery, whereas all calculations concerning visual acuity were done by converting Snellen values to logMAR.

RESULTS

The wavefront optimized ablation group was treated from September 1, 2005 through February 28, 2006, whereas the custom-Q ablation group was treated from March 1, 2006 through August 31, 2006. Forty-six (92%) eyes from the wavefront optimized ablation group and 42 (84%) eyes from the custom-Q ablation group were available for evaluation at 3-month follow-up. Preoperative demographic and refractive data are presented in Table 1, along with the manifest refraction data, BSCVA, asphericity (expressed as Q-factor), spherical aberration, 3rd order higher order aberrations, and total root-mean-square (RMS) higher order aberrations. Four (8%) eyes from the wavefront optimized ablation group and 8 (16%) eyes from the custom-Q ablation group were lost to follow-up. Their baseline data differed insignificantly from their respective groups.

At 3 months after surgery, no eye in either group lost lines of BSCVA, whereas 41 (89.1%) eyes in the wavefront optimized ablation group and 35 (83.3%) eyes in the custom-Q ablation group gained 1 or more lines of BSCVA. Safety index (ratio between the mean postoperative BSCVA and mean preoperative BSCVA) was 1.26 for the wavefront optimized ablation group and 1.29 for the custom-Q ablation group (Fig 1). No statistically significant difference between groups was noted (P=.63).

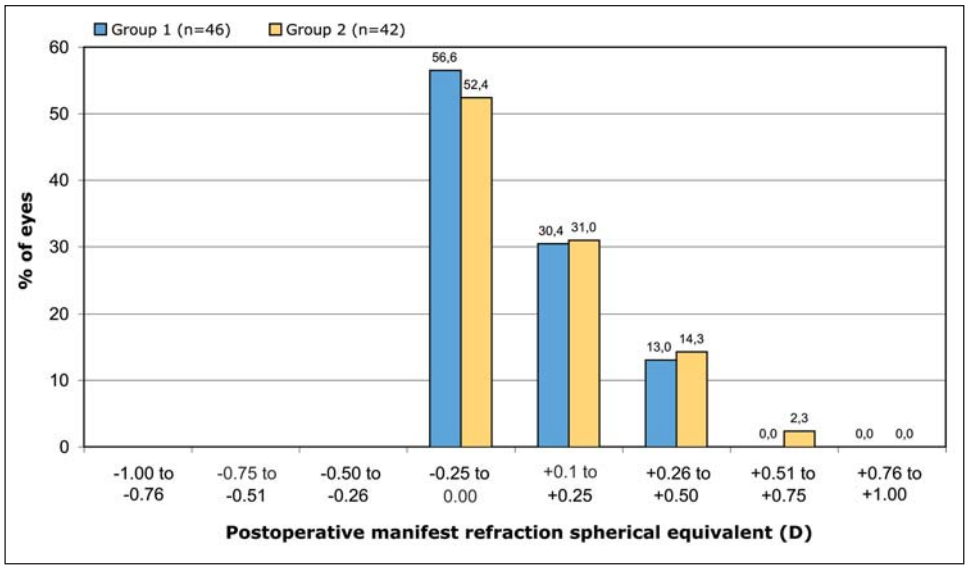

Figure 3. Predictability in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2) 3 months after surgery showing manifest refraction spherical equivalent outcome.

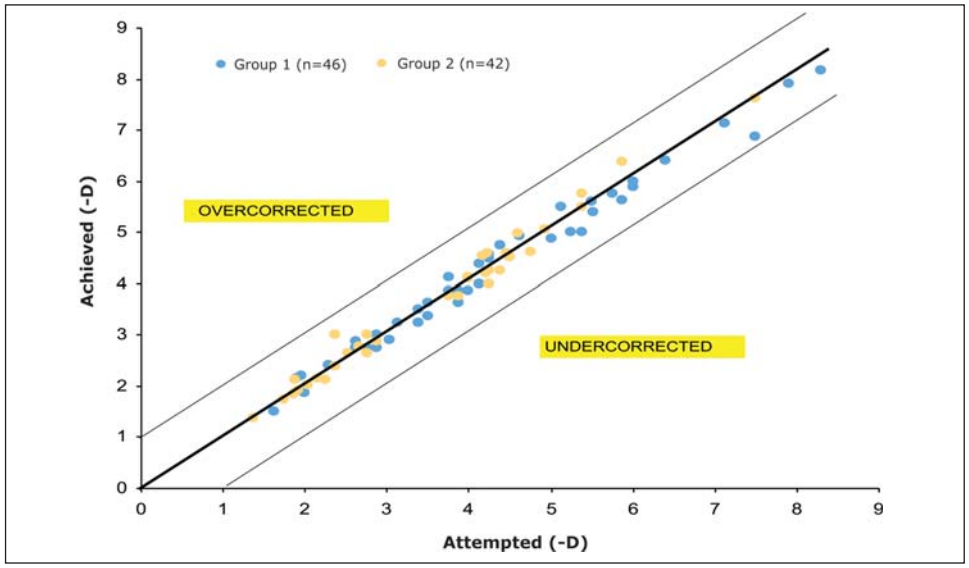

Figure 4. Attempted spherical equivalent refraction versus achieved manifest refraction spherical equivalent in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2) 3 months after surgery.

Forty-one (89.1%) eyes in the wavefront optimized ablation group and 38 (90.5%) eyes in the custom-Q ablation group achieved UCVA better than 20/20, whereas 32 (69.6%) eyes in the wavefront optimized ablation group and 29 (69.1%) eyes in the custom-Q ablation group achieved UCVA better than 20/16. Efficacy index (ratio between the mean postoperative UCVA and mean preoperative BSCVA) was 1.15 for the wavefront optimized ablation group and 1.13 for the custom-Q ablation group (Fig 2). No statistically significant difference was noted between groups (P=.94).

Forty-one (89.1%) eyes in the wavefront optimized ablation group and 36 (85.7%) eyes in the custom-Q ablation group were within 0.25 D of emmetropia, and 42 (91.3%) eyes in the wavefront optimized ablation group and 40 (95.2%) eyes in the custom-Q ablation group were within 0.50 D of emmetropia (Figs 3 and 4). No statistically significant difference between groups was noted (P=.68).

Pre- and postoperative low contrast visual acuity (12.5% contrast) at night and day, with and without glare, for the two groups are shown in Table 2. No statistically significant difference was noted between groups for any low contrast visual acuity modes.

All eyes demonstrated a tendency toward oblate shift after surgery (Fig 5). A marginally statistically significant difference in oblate shift between groups (P=.049) was seen. Mean Q-value changed from −0.33 to 0.06 in the wavefront optimized ablation group and from −0.36 to −0.09 in the custom-Q ablation group. Figure 6 shows the mean Q-shift for two subgroups treated for low and high myopia (division point spherical equivalent refraction −4.00 D). The oblate shift showed a high correlation to the amount of myopic

TABLE 2

Change in Mean Low Contrast Visual Acuity* for Patients in Wavefront Optimized Ablation and Custom-Q Ablation Groups

	Wavefront Optimized Ablation Group			Custom-Q Ablation Group			
Characteristic	**Preoperative**	**Postoperative**	***P* Value†**	**Preoperative**	**Postoperative**	***P* Value†**	***P* Value‡**
Night without glare	20/27	20/26	.16	20/27	20/26	.46	.79
Night with glare	20/27	20/25	.07	20/27	20/26	.57	.48
Day without glare	20/22	20/20	.04	20/22	20/21	.31	.09
Day with glare	20/23	20/21	.06	20/22	20/20	.13	.18

**Mean Snellen low contrast visual acuity (12.5% contrast), converted from logMAR.*
†Preoperative vs postoperative.
‡Postoperative wavefront optimized ablation group vs postoperative custom-Q ablation group.

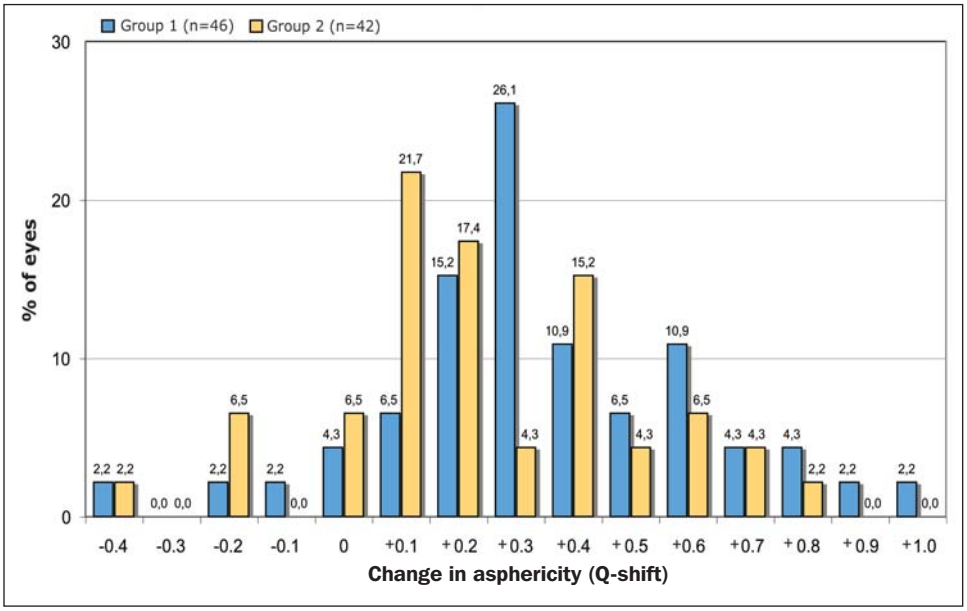

Figure 5. Q-shift (postoperative Q minus preoperative Q) in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2), where negative Q-shift indicates a postoperative asphericity more prolate than preoperative, and positive Q-shift indicates postoperative asphericity less prolate than preoperative.

correction in the wavefront optimized ablation group, but a low correlation in the custom-Q ablation group (three outliers were excluded in both groups) (Figs 7 and 8). Q-targets (applicable only to the custom-Q ablation group) were not achieved (see Fig 8).

Root-mean-square higher order aberrations, spherical aberration, and RMS 3rd order higher order aberrations did not change significantly (Table 3).

Figure 10 shows refractive stability. Figure 11 shows the stability of low contrast visual acuity (12.5% contrast at night without glare) and RMS higher order aberrations at 3 and 6 months after surgery in subgroups of 26 and 18 eyes from the the wavefront optimized ablation and custom-Q ablation groups, respectively.

DISCUSSION

Data on corneal asphericity in the current study were acquired through WaveLight Topolyzer's placido disk–based videokeratography, which provides a map of corneal curvature. Unfortunately, measuring the asphericity with current instruments is not standardized; eg, AstraMax (LaserSight Technologies Inc, Orlando, Fla) gives mean asphericity within a circle of 4.6 mm in diameter, centered on the corneal vertex; Topolyzer calculates the mean asphericity along the flattest and steepest meridians within the apical 30°, providing two values; and Orbscan supplies the information about mean asphericity within a user-defined apical circle. According to the American National Standards Institute (ANSI), mean asphericity should be based on the flattest apical meridian for the central 5.5 mm.[14] All of the mentioned methods provide different values. Additionally, registering asphericity with current technology is more difficult postoperatively than in virgin eyes. This is possibly due to induced corneal morphology changes, result-

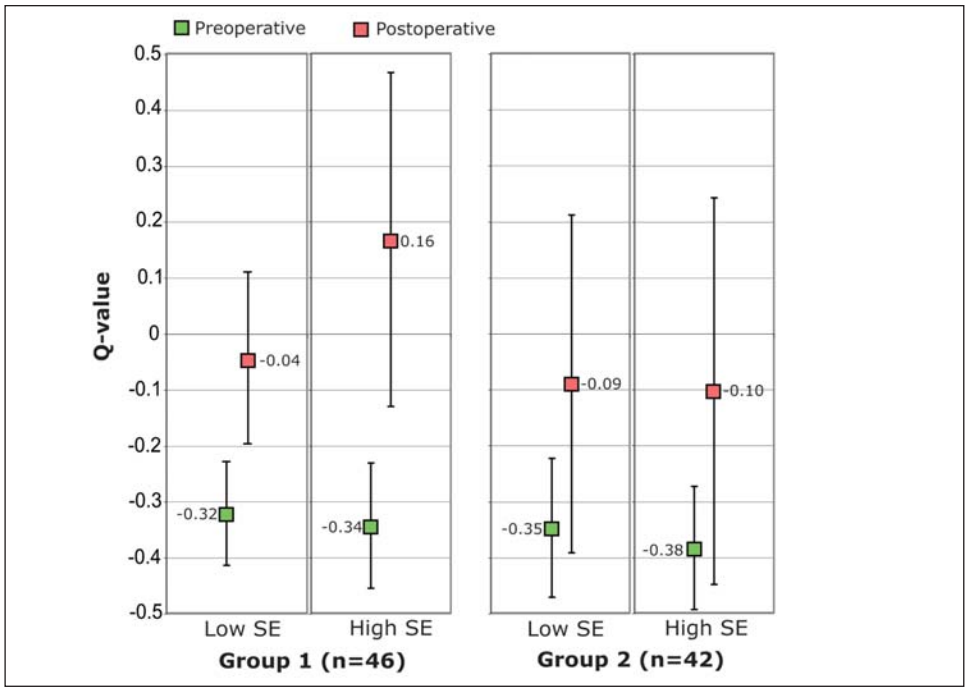

Figure 6. Mean Q-shift in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2) divided in subgroups treated for low myopia (SE <4.00 diopters [D]) and high myopia (SE ⩾4.00 D). Vertical lines represent ±1 standard deviation.

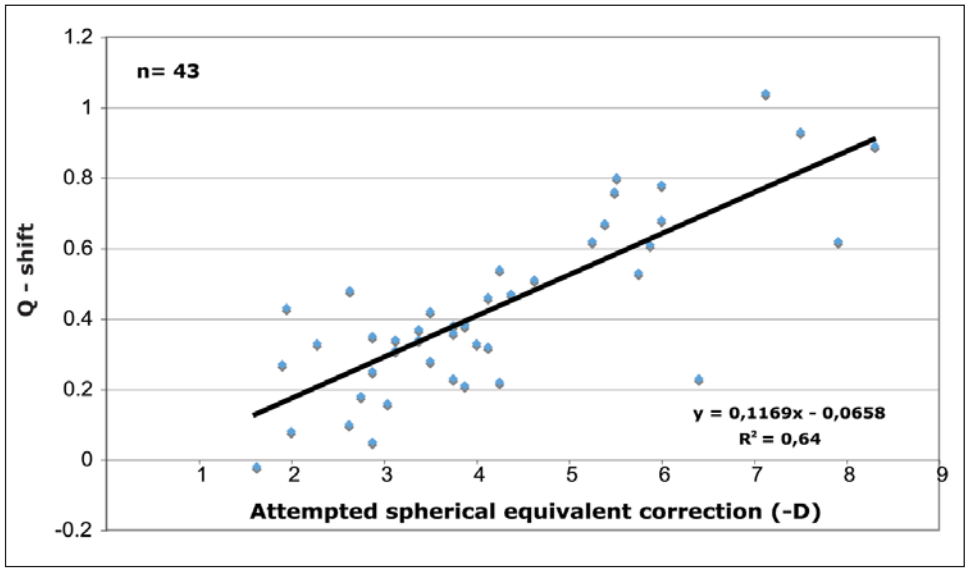

Figure 7. Q-shift versus attempted spherical equivalent refraction correction of myopia in the wavefront optimized ablation group.

ing in decreased reliability of the Q-values (eg, typical measurement error in our material was 0.07 preoperatively and 0.11 postoperatively). Hence, we did not use Q-value data in the current study in any deeper analysis than presented in our results.

It is currently known that for most eyes a negative (prolate) corneal asphericity is required to balance the positive (oblate) asphericity of the crystalline lens[15] to achieve minimal spherical aberration. However, the current standard (non-aspheric) treatments for myopia result in an oblate shift,[5] which disturbs this balance, thereby increasing spherical aberration. A combination of factors such as the decrease in effective radiant exposure to laser energy from the corneal center towards the periphery[16] (due to inclination of corneal surface), reflection losses according to Fresnel's law,[17] and the corneal biomechanical response[3,18] seem to be responsible for the oblate shift. The first two factors are addressed by modern aspheric ablations that feature a correction matrix, which compensates for the reduced laser ablation efficacy in the mid-peripheral cornea.[19] Ablation profiles used in both groups in the current study are compensated for by such a correction matrix[19] and, therefore, the residual oblate shift that our results show is probably, or at least partially, due to a biomechanical response of the cornea in agreement with the study by Koller et al.[7]

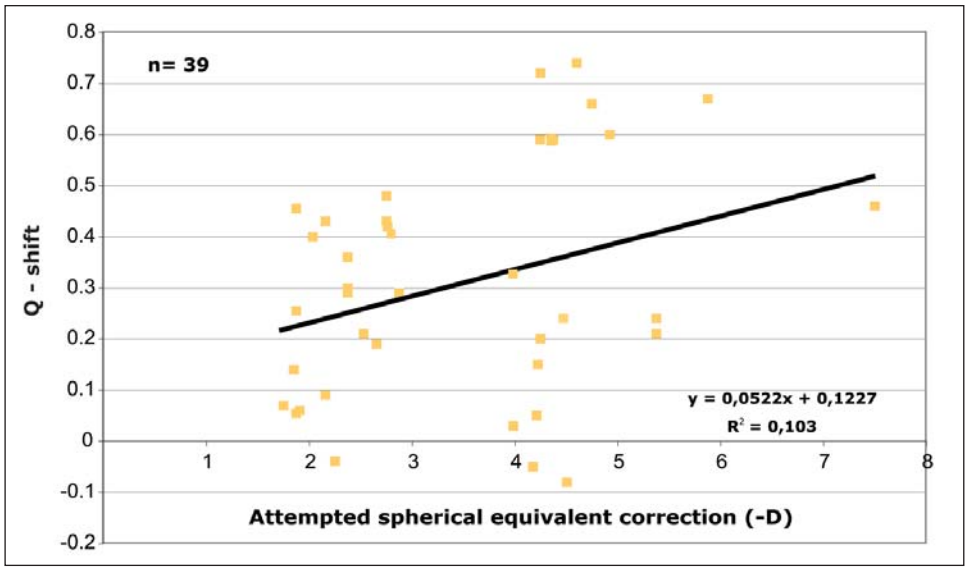

Figure 8. Q-shift versus attempted spherical equivalent refraction correction of myopia in the custom-Q ablation group.

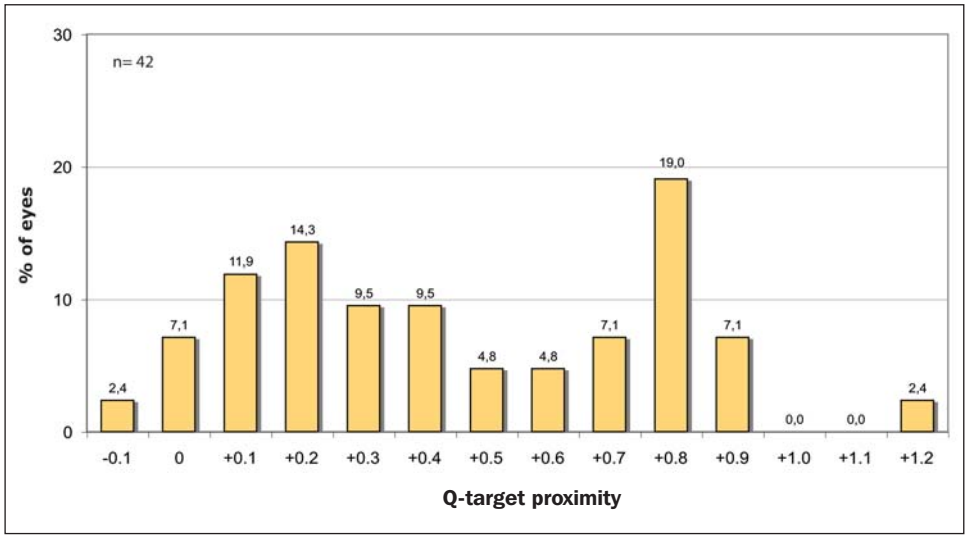

Figure 9. Percentage of eyes in the custom-Q ablation group showing achieved Q-target proximity. Negative values indicate overcorrection (more prolate than intended), whereas positive values indicate undercorrection (less prolate than intended). Q-target was −0.6 in 39 eyes and −0.5 in 3 eyes.

Custom-Q treatments, which were used in the custom-Q ablation group, allowed us to aim for certain asphericity targets. Despite the fact that they were not met (see Fig 9), custom-Q ablations resulted in a smaller mean oblate shift compared to wavefront optimized ablations (see Fig 6), especially for higher degrees of myopia (see Fig 8). This is an improvement compared to ALLEGRETTO's wavefront optimized treatment. The data from the current study concerning Q-shift will help us in building a Q-adjustment nomogram, with the aim of further decreasing the oblate shift in myopic treatments.

Study protocol used two separate Q-targets (−0.5 and −0.6). Only three (7.1%) eyes satisfied our protocol criteria for Q-value of −0.5. The rationale for using two separate Q-targets was to limit possible excessive shift in prolate direction, especially in younger patients with relatively low preoperative Q-values (0 to −0.2) where the preoperative corneal and lenticular asphericity were in balance.[20,21] In retrospect, given the results of the current study where the desired prolateness was clearly not reached, the distinction between Q-targets of −0.6 and −0.5 turned out to be unnecessary.

Only 46 (92%) eyes and 42 (84%) eyes from the wavefront optimized ablation group and custom-Q ablation group, respectively, were available for evaluation mainly due to the long traveling distances in North Norway. We believe this loss to follow-up has not influenced the comparison of pre- and postoperative data as there was not a significant difference in baseline data between the eyes lost to follow-up and the remainder of the respective groups.

This study's 3-month follow-up may appear short, but one must take into account that our treatments were done by surface ablation and the outcomes are expected to change in the course of several months.

TABLE 3

Changes in Aberration Characteristics of Patients in Wavefront Optimized Ablation and Custom-Q Ablation Groups*

	Wavefront Optimized Ablation Group			Custom-Q Ablation Group			
Characteristic	Preoperative (μm)	Postoperative (μm)	*P* Value†	Preoperative (μm)	Postoperative (μm)	*P* Value*	*P* Value‡
Total RMS HOAs	0.20±0.08 (0.10 to 0.51)	0.23±0.09 (0.11 to 0.61)	.13	0.20±0.06 (0.10 to 0.41)	0.22±0.09 (0.13 to 0.53)	.19	.43
Spherical aberration	−0.02±0.06 (−0.22 to 0.11)	−0.03±0.06 (−0.15 to 0.16)	.46	−0.01±0.06 (−0.10 to 0.09)	−0.03±0.04 (−0.11 to 0.03)	.22	.63
RMS 3rd order HOAs	0.16±0.08 (0.05 to 0.47)	0.19±0.09 (0.05 to 0.53)	.17	0.18±0.09 (0.06 to 0.54)	0.19±0.08 (0.09 to 0.41)	.25	.55

HOAs = higher order aberrations
**Values represented as mean±standard deviation (range).*
†Preoperative vs postoperative.
‡Postoperative wavefront optimized ablation group vs postoperative custom-Q ablation group.

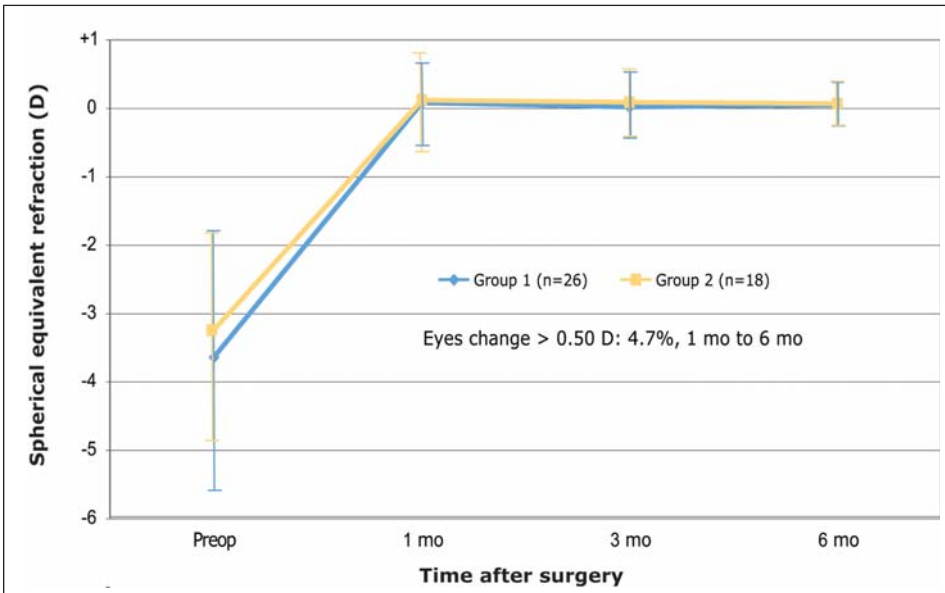

Figure 10. Stability of mean manifest refraction spherical equivalent in subgroups of the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2). Vertical lines represent ±1 standard deviation.

However, our experience with the current laser, which produces wide and smooth ablations, is that results stabilize before 3 months postoperatively. To support this statement, we analyzed 6-month follow-up of subgroups of 26 eyes from the wavefront optimized ablation group and 18 eyes from the custom-Q ablation group (see Figs 10 and 11).

Our protocol included application of "frozen BSS popsicle" before and after epithelial removal and after laser ablation. Currently, no published study in the peer-reviewed literature addresses the use of the "frozen BSS popsicle" technique, but various authors have presented this technique at numerous international meetings as well as in non-peer-reviewed literature.[22,23]

After receiving confirmation from WaveLight that it would not interfere with the laser's eye tracking, a globe fixation ring was applied in the current treatments to maintain the initial eye alignment and prevent decentration due to possible patient fixation loss during ablation. Bueeler et al[11] showed that an ablation displacement ⩾0.21 mm, which will occur due to parallax effect in a non-fixating eye with a globe rotation ⩾3.25°, will induce visually significant higher order aberrations. With the same amount of globe rotation, pupil horizontal displacement (as "seen" by the eye tracker) will be ⩾0.62 mm. However, the current pupil-tracking eye trackers will not interupt the ablation until a horizontal pupil displacement of at least 1 mm occurs. A detailed analysis of the implica-

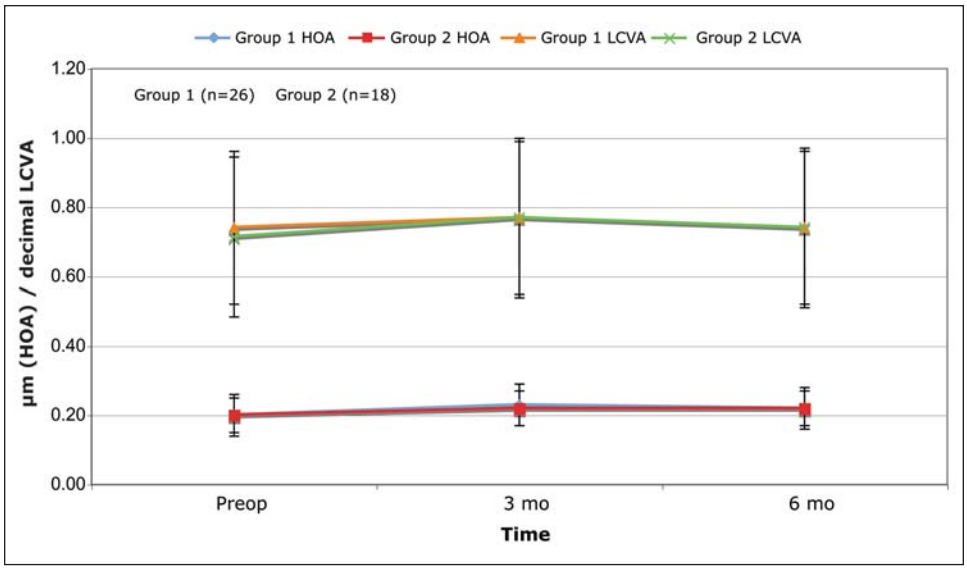

Figure 11. Stability of mean root-mean-square high order aberrations (RMS HOA) and mean low contrast visual acuity (LCVA) in the wavefront optimized ablation group (group 1) and custom-Q ablation group (group 2). Vertical lines represent ±1 standard deviation.

tions of manual globe fixation will be addressed in a future article.

According to the calculations of Gatinel et al,[24] an intentional increase in prolate asphericity caused by a mid-peripheral increase in ablation depth results in a decrease in myopic correction. To compensate for this, a deeper central ablation is necessary in aspheric ablations. However, in our previous clinical experience with custom-Q ablation, the built-in compensation is too large. Therefore, to avoid overcorrection, we made a nomogram adjustment by reducing the amount of treated sphere, as previously described in Patients and Methods. This provided excellent predictability, which is comparable to recently published LASIK outcomes for low to moderate myopic treatments in virgin eyes.[25,26] The nomogram adjustment (ranging from 0.10 to 0.80 D) depended on the desired Q-target, the preoperative Q-value, and the amount of treated myopia/astigmatism. The adjustment increased with the increase of targeted prolateness and the amount of myopic correction, whereas it decreased with the amount of astigmatism correction and with more oblate preoperative asphericity. We believe this nomogram adjustment had an insignificant influence on the amount of the oblate shift.

Because we treated only virgin eyes with good preoperative contrast sensitivity and a low preoperative level of higher order aberrations, our aim was to eliminate the patient's spherocylindrical error without disturbing the remainder of the corneal optics significantly. Koller et al[7] used the same laser platform and found a much larger increase in the 3rd order higher order aberrations (from 0.181±0.072 µm before surgery to 0.296±0.115 µm after surgery) in eyes treated with custom-Q ablation, compared to wavefront-guided treatments (from 0.182±0.094 µm before surgery to 0.192±0.088 µm after surgery). Tran and Shah[27] compared WaveLight wavefront optimized treatments and LADARVision4000 (Alcon Laboratories Inc, Ft Worth, Tex) wavefront-guided treatments and found significantly more induced 3rd order higher order aberrations with the former. Both of our groups were treated with non-wavefront-guided ablations. The 3rd order higher order aberrations in both groups changed only insignificantly (from 0.163±0.081 µm before surgery to 0.191±0.092 µm after surgery in the wavefront optimized group and from 0.182±0.092 µm before surgery to 0.193±0.085 µm after surgery in the custom-Q group). Hence, our results in both groups were more comparable to Koller et al[7] and Tran and Shah's[27] wavefront-guided treatments than with their wavefront optimized treatments. The reason for this may be our centration of the ablation on the corneal vertex, the implications of which will be addressed in more detail in a future article.

Our total RMS higher order aberrations, spherical aberration, and the 3rd order higher order aberrations increased very little and resulted in well-preserved, low contrast visual acuity under light and dark conditions, with and without glare (a finding comparable to the study by Koller et al[7]), and a statistically significant correlation between the postoperative Q-values and low contrast visual acuity has not been found. Tuan and Chernyak[14] did not find such a correlation either and concluded that "an oblate cornea is as likely to produce high-quality vision as a prolate one." Other explanations may be that low contrast visual acuity is a subjective measurement dependent on a number of interrelated factors and the low quality of postoperative asphericity data.

Our results showed almost universal oblate Q-shift in both groups (see Fig 5). The shift was less in the custom-Q group, but the difference between groups was just marginally statistically significant (P=.049) and did not result in any significant difference in postoperative spherical aberration or low contrast visual acuity. This may be caused either by the insufficient measurement reliability of our asphericity and wavefront aberrometry, or by a small influence of the achieved Q-value changes on the spherical aberration and low contrast visual acuity.

It is uncertain whether more prolate Q-targets would further diminish or eliminate the remaining oblate shift found in our custom-Q treatments. We are limited to what we can achieve by the Q-target adjustment, especially if we bear in mind that a part of the oblate shift most likely occurs due to biomechanical response of the cornea, which may need to be counteracted by a different approach. However, with the custom-Q treatments we have a new possibility to better control the oblate shift. Hopefully, in the future it will be possible to achieve specific Q-targets resulting in minimal spherical aberration.

REFERENCES

1. Seiler T, Wollensak J. Myopic photorefractive keratectomy with the excimer laser: one-year follow-up. *Ophthalmology.* 1991;98:1156-1163.
2. Oshika T, Klyce SD, Applegate RA, Howland HC, El Danasoury MA. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. *Am J Ophthalmol.* 1999;127:1-7.
3. Roberts C. The cornea is not a piece of plastic. *J Refract Surg.* 2000;16:407-413.
4. Hjortdal JØ, Olsen H, Ehlers N. Prospective randomized study of corneal aberrations 1 year after radial keratotomy or photorefractive keratectomy. *J Refract Surg.* 2002;18:23-29.
5. Anera RG, Jiménez JR, Jiménez del Barco L, Bermudez J, Hita E. Changes in corneal asphericity after laser in situ keratomileusis. *J Cataract Refract Surg.* 2003;29:762-768.
6. Marcos S, Cano D, Barbero S. Increase in corneal asphericity after standard laser in situ keratomileusis for myopia is not inherent to the Munnerlyn algorithm. *J Refract Surg.* 2003;19: S592-S596.
7. Koller T, Iseli HP, Hafezi F, Mrochen M, Seiler T. Q-factor customized ablation profile for the correction of myopic astigmatism. *J Cataract Refract Surg.* 2006;32:584-589.
8. Mastropasqua L, Toto L, Zuppardi E, Nubile M, Carpineto P, Di Nicola M, Ballone E. Photorefractive keratectomy with aspheric profile of ablation versus conventional photorefractive keratectomy for myopia correction: six-month controlled clinical trial. *J Cataract Refract Surg.* 2006;32:109-116.
9. Stojanovic A, Nitter TA. Correlation between ultraviolet radiation level and the incidence of late-onset corneal haze after photorefractive keratectomy. *J Cataract Refract Surg.* 2001;27:404-410.
10. Stojanovic A, Ringvold A, Nitter T. Ascorbate prophylaxis for corneal haze after photorefractive keratectomy. *J Refract Surg.* 2003;19:338-343.
11. Bueeler M, Mrochen M, Seiler T. Maximum permissible lateral decentration in aberration-sensing and wavefront-guided corneal ablation. *J Cataract Refract Surg.* 2003;29:257-263.
12. Ciccio AE, Durrie DS, Stahl JE, Schwendeman F. Ocular cyclotorsion during customized laser ablation. *J Refract Surg.* 2005;21:S772-S774.
13. Vinciguerra P, Azzolini M, Airaghi P, Radice P, De Molfetta V. Effect of decreasing surface and interface irregularities after photorefractive keratectomy and laser in situ keratomileusis on optical and functional outcomes. *J Refract Surg.* 1998;14:S199-S203.
14. Tuan M, Chernyak D. Corneal aspericity and visual function after wavefront-guided LASIK. *Optom Vis Sci.* 2006;83:605-610.
15. Atchinson D, Smith G. Refractive components: cornea and lens. In: Atchinson D, Smith G, eds. *Optics of the Human Eye.* Edinburgh, United Kingdom: Butterworth-Heinemann; 2003:11-20.
16. Mrochen M, Seiler T. Influence of corneal curvature on calculation of ablation patterns used in photorefractive laser surgery. *J Refract Surg.* 2001;17:S584-S587.
17. Ginis HS, Katsanevaki VJ, Pallikaris IG. Influence of ablation parameters on refractive changes after phototherapeutic keratectomy. *J Refract Surg.* 2003;19:443-448.
18. Roberts C. Biomechanics of the cornea and wavefront-guided laser refractive surgery. *J Refract Surg.* 2002;18:S589-S592.
19. Mrochen M, Donitzky C, Wüllner C, Löffler J. Wavefront-optimized ablation profiles: theoretical background. *J Cataract Refract Surg.* 2004;30:775-785.
20. Fujikado T, Kuroda T, Ninomiya S, Maeda N, Tano Y, Oshika T, Hirohara Y, Mihashi T. Age-related changes in ocular and corneal aberrations. *Am J Ophthalmol.* 2004;138:143-146.
21. Amano S, Amano Y, Yamagami S, Miyai T, Miyata K, Samejima T, Oshika T. Age-related changes in corneal and ocular higher-order wavefront aberrations. *Am J Ophthalmol.* 2004;137:988-992.
22. Trottler WB. Minimizing postoperative discomfort. *Cataract & Refractive Surgery Today.* January 2007:77-78.
23. Pallikaris I, McDonald M, Cross W, Durrie D, Camellin M, Vinciguerra P, Katsanevski V, Volpicelli, M, Kantor R. Epi-LASIK: A round table discussion. *Supplement to Cataract & Refractive Surgery Today.* May 2005:1-11.
24. Gatinel D, Malet J, Hoang-Xuan T, Azar DT. Analysis of customized corneal ablations: theoretical limitations of increasing negative asphericity. *Invest Ophthalmol Vis Sci.* 2002;43:941-948.
25. Subbaram MV, MacRae S, Slade SG, Durrie DS. Customized LASIK treatment for myopia: relationship between preoperative higher order aberrations and refractive outcome. *J Refract Surg.* 2006;22:746-753.
26. Du CX, Yang YB, Shen Y, Wang Y, Dougherty PJ. Bilateral comparison of conventional versus topographic-guided customized ablation for myopic LASIK with the NIDEK EC-5000. *J Refract Surg.* 2006;22:642-646.
27. Tran DB, Shah V. Higher order aberrations comparison in fellow eyes following IntraLase LASIK with WaveLight Allegretto and CustomCornea LADARVision4000 systems. *J Refract Surg.* 2006;22:S961-S964.