Topographically guided laser in situ keratomileusis for myopia using a customized aspherical treatment zone

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PURPOSE: To assess the efficacy, predictability, safety, and quality-of-life effects of topography-guided laser in situ keratomileusis (LASIK) for the correction of myopia with astigmatism using the EC-5000 CXII excimer laser equipped with a customized aspheric treatment zone algorithm.

SETTING: Ophthalmology clinics in the United States and Mexico.

METHODS: In a multicenter United States Food and Drug Administration study of topography-guided LASIK, 4 centers enrolled 135 eyes with a spherical manifest refraction error ranging from −0.50 to −7.00 diopters (D) and astigmatism ranging from 0.50 to 4.00 D. All eyes were targeted for emmetropia. Refractive outcomes, higher-order aberrations (HOAs), and contrast sensitivity were analyzed preoperatively and postoperatively. Patient satisfaction was assessed using 2 questionnaires.

RESULTS: Six months postoperatively, the mean manifest refraction spherical equivalent in all eyes was −0.09 D ± 0.31 (SD); of the 131 eyes, 116 (88.55%) had an uncorrected visual acuity of 20/20 or better and 122 (93.13%) had an MRSE within ±0.50 D. The best spectacle-corrected visual acuity (BSCVA) increased by 2 or more lines in 21 (16.03%) of 131 eyes; no eye lost 2 lines or more of BSCVA. The total ocular HOA increased by 0.04 μm. Patients reported significantly fewer night driving and glare/halo symptoms postoperatively than preoperatively.

CONCLUSION: Use of a customized aspherical treatment zone in eyes with myopia and astigmatism was safe, effective, and predictable and reduced symptoms associated with night driving, glare, and halos.

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Customized corneal ablations to treat refractive errors using laser in situ keratomileusis (LASIK) or photorefractive keratectomy (PRK) can be based on corneal topography, whole-eye wavefront, or corneal wavefront. Topography-based ablations treat irregularities in corneal elevation in addition to the spherocylindrical refractive error. Alternatively, wavefront-based treatments address the wavefront aberrations of the cornea or of the entire eye in addition to the refractive error. Several studies[1–9] show that topography-based ablations are safe and effective for the treatment of primary myopia and astigmatism.

Custom ablation, whether topography based or ocular-wavefront based, was developed to address disadvantages of conventional spherocylindrical ablation. The unoperated, normal cornea is prolate, with an average positive asphericity of approximately +0.24. Conventional excimer laser ablations for myopia create an oblate cornea and induce positive spherical aberration, which can cause bothersome mesopic and scotopic symptoms such as glare, halos, and difficulty driving at night.[10–12]

The advantages of topography-guided treatments over wavefront-guided treatments are that topography-guided treatments deliver the treatment based on the shape of the corneal surface, which (with the tear film) is the major refractive surface of the eye; topographers can measure and the excimer laser can treat a wider area because topographers measure a much wider diameter on the cornea (out to 11.50 mm) than aberrometers, which are limited by a 5.0 or 6.0 mm pupil aperture; the treatments are not confounded by the presence of a cataract, an intraocular lens, or significant refractive gradients, as are whole-eye aberrometry measurements; topographers have a higher number of data points than aberrometers; the cornea

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is generally stable throughout life so a topography-guided treatment is also more likely to be more stable than aberrometry measurements that take into account lenticular aberrations, which change throughout life.

The disadvantage of topography-based treatments is that they do not incorporate all refracting elements of the eye, which leads to decoupling of lenticular from corneal aberrations; thus, the lenticular aberrations are not treated, which may alter visual quality postoperatively. The positive corneal spherical aberration and the negative lenticular spherical aberration compensate for each other in the normal myopic eye up to approximately age 30 years; thereafter, the lens develops more positive spherical aberration.[13] Therefore, treating only the corneal spherical aberration may unmask lenticular spherical aberrations, which had could cause halos at night.[13] Aspherical treatment zones use an ablation algorithm that reduces the effect of this decompensation by inducing less change in corneal curvature and less spherical aberration.[14]

The customized aspheric treatment zone (CATz) ablation algorithm of the EC-5000 CXII excimer laser (Nidek Co. Ltd.) uses aspherical treatment zones. In the algorithm, the aspherical ablation is combined with the treatment of corneal elevation irregularities. The algorithm uses a combination of optical and transition ablation zones that gradually taper the corneal curvature paracentrally and peripherally, creating a single treatment zone, as defined by Hori-Komai et al.[14] Thus, the stated diameters of the optical zone (OZ) and transition zone (TZ) are not meaningful because all blend together to form a single treatment zone or ablation zone.

The current study evaluated the efficacy, predictability, safety, wavefront induction, and patient satisfaction with LASIK to correct low to moderate myopia with astigmatism using the CATz algorithm of the EC-5000 CXII excimer laser in an ongoing United States Food and Drug Administration (FDA) trial.

PATIENTS AND METHODS

Patient Population and Examinations

Four investigative sites were involved in this FDA trial. Institutional review board approval was obtained for all investigative sites. Written informed consent was obtained from all study patients.

One hundred thirty-five eyes of 68 patients (1 patient had only 1 eye treated) were treated with LASIK for myopia with astigmatism. All patients included in the study were 21 years or older and had a spherical manifest refraction error ranging from −0.50 to −7.00 diopters (D) with 0.50 to 4.00 D of astigmatism. Patients were enrolled in the study if they had had a stable refraction for 1 year before the study and had discontinued contact lens use for 3 to 28 days (depending on contact lens type) before the preoperative examination to stabilize keratometry and corneal topography. Patients were required to have normal keratometry and topography with less than 10 µm of corneal irregularity. The volume of corneal irregularity was determined using Final Fit ablation planning software (Nidek Co. Ltd.). Patients who had an acute illness, a calculated postoperative corneal bed thickness less than 250 µm after ablation, a preoperative central corneal thickness less than 475 µm, previous ophthalmic surgery, or abnormal corneal topography (eg, keratoconus suspect, pellucid marginal degeneration) were excluded from the study.

The preoperative ophthalmic examination included uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), manifest refraction, photopic and mesopic contrast sensitivity testing with and without glare conditions, slitlamp evaluation, corneal topography and aberrometry (OPD-Scan, Nidek Co. Ltd.) (acquired 3 times), pupillometry (OPD-Scan), ultrasound pachymetry (instruments varied by site), keratometry, and a dilated fundus evaluation by the surgeon. The same measurements (with the exception of dilated fundoscopy, pupillometry unless warranted, and contrast sensitivity at 6 months only) were performed 1 week and 1, 3, and 6 months postoperatively.

Wavefront Measurements

Aberrometry was performed using the OPD-Scan device, which measures ocular aberrometry using the principle of spatial dynamic skiascopy; it measures 1440 data points within a 6.0 mm pupil aperture. Pharmacologic pupil dilation is not required for measurement. Ocular higher-order wavefront measurements were performed and reported to the sixth Zernike level. Fourth-order spherical aberration is reported in this study.

Contrast Sensitivity

Contrast sensitivity was evaluated preoperatively and 6 months postoperatively with and without glare under mesopic (3 cd/m^2) and photopic (85 cd/m^2) conditions. Testing was performed using the Optec 6500 vision tester and the Functional Acuity Contrast Test (FACT) chart (both Stereo Optical Co. Inc.) with sine wave gratings. The FACT chart tests at 5 spatial frequencies (1.5, 3, 6, 12, and 18 cycles per

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degree [cpd]) and 9 levels of contrast that increase in contrast in equal 0.15 log units from column 1 through column 9 for each spatial frequency. The Optec 6500 is calibrated by the manufacturer to provide photopic and mesopic test conditions and has a built-in glare source that is preset to deliver 1 lux of glare luminance under mesopic test conditions. For the test, the patient reports the orientation of the grating (right, up, or left). The test was scored by assigning the corresponding percentage contrast value for the target to the last correct grating (target) seen at each spatial frequency according to a chart provided by the manufacturer. Clinically significant changes in contrast sensitivity were defined as a greater than 0.3 log unit increase (gain) or decrease (loss) at 2 or more spatial frequencies.[15]

Subjective Questionnaires

The patients' quality of vision and subjective response were assessed using a 10-point self-administered questionnaire designed for this study and the validated Refractive Status and Vision Profile (RSVP) questionnaire.[16] For the questionnaire designed for this study, patients were asked to rate the presence or absence of each visual complaint at baseline and at each postoperative visit beginning at 1 month. Patients were instructed to rate the absence of a complaint as "none"; the presence of a complaint was rated as "mild," "moderate," "marked," or "severe." A clinically significant change was defined as a change of 10% or greater in the proportion of patients reporting symptoms that were moderate to severe postoperatively compared with baseline. Due to the large sample size, there was a good chance that some differences in the parameters of the postoperative results and the preoperative results would be statistically significant. This significance would not be due to patient physiology or the laser but rather to the number of parameters being tested and the large sample size. To avoid having to explain spurious results, differences in parameters that would be meaningful or significant from the clinical perspective were defined during the study protocol development stage. The thought was that a 1% change (positive or negative) in a parameter is generally disregarded as "noise" in the data by most clinicians. The consensus was that a 10% change would remove the effect of the noise in the data and would be sufficient in magnitude that clinicians would regard it as clinically significant. Although an arbitrary definition, the advantage is that it obviated the need to perform several unnecessary statistical tests on parameters that were not germane to the approval of the laser. This was used as the basis for determining a clinically significant difference from baseline to postoperative visits.

The RSVP questionnaire measures self-reported vision-related health status in patients with refractive errors. Scores on the overall RSVP scale and on 8 RSVP subscales (functioning, driving, concern, expectations, symptoms, glare, optical problems, problems with corrective lenses) are calculated based on 42 items. The subscales are designed to assess the change in clinical measures associated with refractive surgery. Thus, the primary analysis of the questionnaire data is to assess the differences between a post-score and the pre-score for each subscale (excluding expectations). On the scales, higher scores indicate greater dissatisfaction or a greater negative outcome. Thus, a negative difference in a subscale score is desirable. The RSVP questionnaire measures clinical outcomes including a range of visual, functional, and psychological changes in refractive error and visual function and quality of life that are likely to be important to patients.

In this study, the RSVP questionnaire was administered at baseline and at each postoperative visit beginning at 1 month to evaluate patient satisfaction, use of corrective lenses (spectacles or contact lenses, if appropriate), quality of vision, and quality of life. The number of respondents for each subscale varies based on whether the subscale question applies to a particular patient. For example, if the subscale question asks the patient about the use of glasses and the patient does not wear glasses, the patient does not answer that question. A negative number difference from baseline indicates an improvement in the subscale. A difference of 6 or more points on the composite score is considered a clinically significant change.

Treatment Simulations and Ablation Data Preparation

Before treatment simulation, the operating surgeon evaluated the Placido disk mires from corneal topography for tear-film dysfunction such as dry spots, lacrimal lake, or mucus build up that would generate spurious data. The surgeon selected the most regular of the 3 topography measurements from the OPD-Scan device. All treatments were simulated and the shot data prepared using Final Fit ablation planning software. The treatment planning software allows the surgeon to modify parameters including OZ, TZ, laser ablation profile, and amount of corneal irregularity treatment. Corneal irregularity was quantified using the irregularity field (IRR max) in the ablation simulation maps. Once the treatment parameters were finalized, a simulation of postoperative corneal topography was generated and the shot data were exported to the CXII excimer laser. Asymmetric irregularities detected with corneal topography were treated using the multipoint spot ablation.

The custom aspherical ablation algorithm used differs from a conventional spherocylindrical ablation in 2 ways. First, the TZ that lies between the outer edge of the OZ and the outermost area of the entire ablation zone is adjustable based on the diameters of the OZ and TZ that are selected. In the TZ, beginning at the outside diameter of the OZ, the refractive ablation continues with an aspheric algorithm that decreases the volume of ablation gradually as the ablation expands peripherally to minimize the rate of change in corneal curvature. The use of an OZ with the TZ architecture described above is called the optimized aspheric treatment zone (OATz).[14] The EC-5000 CXII has 7 profiles for the TZ, and OATz profile 5 was used for all treatments. Second, the treatment of corneal surface irregularities in addition to OATz is designated by the ablation algorithm.

All eyes were targeted for emmetropia, with sphere and cylinder values based on the preoperative manifest refraction. The corneal irregularity simulated with the Final Fit ablation planning software could not exceed an elevation of 10 μm. Based on the manufacturer's recommendation, 80% of the calculated irregularity treatment was selected. This conservative calculation prevented overtreatment in eyes with prominent irregularity.

In this study, all eyes had the refractive treatment using a 5.0 mm diameter OZ and an 8.5 mm TZ. Corneal surface irregularities were treated using a 6.0 mm OZ and an 8.5 mm TZ. The combination of OZs and TZs and the irregularity ablation constituted the total TZ and created the refractive correction of the eye. The sphere and cylinder input values

were not modified according to the magnitude or pattern of corneal irregularity. A satisfactory simulated result was one in which the corneal topography minimized the gradient of corneal curvature change, maximized the effective OZ, and reduced or eliminated the corneal irregularities yet maintained adequate residual corneal tissue in the stromal bed.

Surgical Technique

Eyes were prepared for surgery as customary at each center. One or 2 drops of a topical anesthetic agent were instilled, and a sterile drape was used to isolate the surgical field. A lid speculum was inserted to allow maximum exposure of the globe. Additional topical anesthetic agent was applied. Automated mechanical microkeratomes were used to create nasal or superior lamellar corneal hinged flaps that were 9.0 mm or larger to accommodate the TZ ablation. Each site used a different microkeratome; the microkeratomes were the MK-2000, (Nidek Co. Ltd.), Moria M2 (Moria), Amadeus (Zeimer Ophthalmic Systems), and Hansatome (Bausch & Lomb).

Proper alignment of the eye with the laser was achieved with a 200 Hz infrared eye tracker built into the laser console and centered on the pupil. Torsional errors were corrected by enabling the torsion error detection function of the laser before the ablation for improved registration. The flap was lifted, the tracker activated, and the excimer laser ablation was delivered to the stoma. Patients fixated on a red fixation light, coaxial with the surgeon's line of sight and the excimer laser beam, throughout the ablation, keeping the tracker centered on the pupil. The flap was repositioned and the interface irrigated with a balanced salt solution, removing any debris; the flap was then smoothed into position. Patients were discharged with instructions to instill topical fluoroquinolone antibiotic and corticosteroid drops 4 times a day for 5 days.

Excimer Laser Ablation

The laser ablation algorithms used a rotating scanning slit and expanding diaphragm delivery system to correct sphere and cylinder. The ablation was performed in 3 automated successive steps: the sphere first, the cylinder next, and then the multipoint ablation using a 1.0 mm spot of the multipoint ablation hardware system to correct the corneal irregularities.

Refractive Stability

Postoperative refractive stability was evaluated by assessing the percentage of eyes with a change in manifest refraction spherical equivalent (MRSE) of 1.00 D or less at 3-month intervals as well as a mean rate of change in MRSE of 0.50 D or less per year (0.04 D/month).

Data Analysis

Refractive outcomes, changes in higher-order aberrations (HOAs), contrast sensitivity, and the results of the RSVP and custom questionnaires were analyzed by a biostatistician using SAS software (SAS Institute, Inc.). Pooled analysis of the entire cohort was also performed. Data from 1 week and 1, 3, and 6 months after LASIK are presented. A P value less than 0.05 was considered statistically significant.

RESULTS

The mean age of the patients was 36 years $\pm$ 11.2 (SD) (range 23 to 64 years). Preoperatively, the mean MRSE was -3.57 ± 1.45 D (range -1.25 to -6.87 D), the mean sphere was -3.06 ± 1.39 D (range -1.00 to -6.00 D), and the mean cylinder was -1.02 ± 0.64 D (range -0.50 to -3.50 D).

Refractive and Visual Acuity Outcomes

Table 1 shows the refractive and visual acuity outcomes in all eyes. The percentage of eyes with a UCVA of 20/20 or better 6 month postoperatively was higher than the percentage of eyes that had a BSCVA of 20/20 or better preoperatively (Figure 1). At 6 months, no eye had a loss of 2 or more lines of BSCVA (Figure 2). The BSCVA increased by 2 or more lines in 21 (16.03%) of 131 eyes (Figure 2). Figure 3 shows the attempted versus achieved refractive results in all eyes 6 months postoperatively. The defocus equivalent was 0.50 D or better in 114 (87%) of 131 eyes (Figure 4).

There was a mean change in MRSE of -0.03 ± 0.39 D between 1 week and 1 month postoperatively. The MRSE changed by -0.02 D from 1 month to 3 months and by -0.04 D from 3 months to 6 months (Figure 5). Refractive stability was reached by 3 months.

Ocular Wavefront Aberrations

The mean root-mean-square (RMS) value for the total HOAs was 0.250 ± 0.103 µm preoperatively and 0.290 ± 0.099 µm 6 months postoperatively ($P = .002$). The mean spherical aberration was 0.003 ± 0.065 µm preoperatively and 0.056 ± 0.069 µm at 6 months ($P = .000$) and the mean coma, 0.107 ± 0.062 µm and 0.137 ± 0.088 µm, respectively ($P = .001$).

Contrast Sensitivity

Two of the 4 sites completed the test procedures according to protocol in all treated eyes. One site performed the testing but, by error, omitted the baseline glare testing. Another site performed the test binocularly instead of monocularly for all eyes. The other 2 sites recorded contrast sensitivity in the treated eyes tested monocularly at baseline and 6 months postoperatively under mesopic and photopic illumination without glare (104 eyes) and with glare (67 eyes).

Table 2 shows the photopic contrast sensitivity with and without glare at baseline and 6 months after surgery. There was a gain in mean photopic contrast sensitivity with and without glare at all spatial frequencies except 12 cpd without glare, at which there was a statistically insignificant loss in contrast (1.3%)

Table 1. Refractive and visual acuity outcomes.

	Mean ± SD			Eyes (%)	
Postop Follow-up	MRSE (D)	Sphere (D)	Cylinder (D)	MRSE Within ±0.50 D	UCVA 20/20 or Better
1 week (n = 133)	+0.09 ± 0.38	0.11 ± 0.39	−0.21 ± 0.27	116 (87.22)	104 (78.20)
1 month (n = 135)	−0.04 ± 0.31	−0.07 ± 0.31	−0.23 ± 0.25	126 (93.33)	109 (80.74)
3 months (n = 127)	−0.06 ± 0.29	−0.04 ± 0.32	−0.22 ± 0.26	118 (92.90)	110 (86.61)
6 months (n = 131)	−0.09 ± 0.31	−0.06 ± 0.31	−0.25 ± 0.27	122 (93.13)	116 (88.55)

MRSE = mean refractive spherical equivalent; UCVA = uncorrected visual acuity

(P = .64). There was a statistically significant improvement in photopic contrast at 3 cpd (P = .02) and at 6 cpd (P = .00) with glare.

Table 3 shows the mesopic contrast sensitivity with and without glare at baseline and 6 months after surgery. There was gain in mean mesopic contrast sensitivity with and without glare at all but the highest spatial frequencies; that is, at 12 cpd without glare and 18 cpd with and without glare. Only the decrease at 18 cpd without glare was statistically significant (P = .03). The improvement in mean mesopic contrast sensitivity with glare was statistically significant at 1.5 cpd and 3 cpd (both P = .02).

Using the criterion of a clinically significant change in contrast sensitivity as a change greater than 0.3 log units at 2 or more spatial frequencies, 14 (21%) of 67 eyes had a clinically significant improvement in mesopic contrast sensitivity with glare. Fourteen percent (14%) of 104 eyes had a clinically significant improvement in mesopic contrast sensitivity without glare. Four (6%) of 67 eyes had a clinically significant decrease in mesopic contrast sensitivity without glare, and 6 (5.80%) of 104 had a clinically significant decrease in mesopic contrast sensitivity without glare. Fourteen (21%) of 67 eyes had a clinically significant improvement in photopic contrast sensitivity with glare, and 11 (11%) of 104 eyes had a clinically significant improvement in photopic contrast sensitivity without glare. Six (9%) of 67 eyes had a clinically significant decrease in photopic contrast sensitivity without glare, and 10 (9%) of 104 eyes had a clinically significant decrease in photopic contrast sensitivity without glare.

Patient Satisfaction

Table 4 shows the changes from baseline to 3 months (time of refractive stability) in the severity of patient symptoms reported on the self-administered questionnaire designed for this study. There was a statistically significant (P = .00) and clinically significant improvement in night driving, with 23.0% fewer patients reporting moderate or severe difficulty driving at night postoperatively. The proportion of eyes with marked or severe dryness increased by 3.3% at 3 months, which was a statistically significant (P = .04), but not clinically significant, change.

Table 5 shows the changes in the scores 3 months and 6 months after surgery for each subscale of the RSVP questionnaire. At 3 months (time of refractive stability), all subscales and total score changes from baseline (except glare) were statistically significant

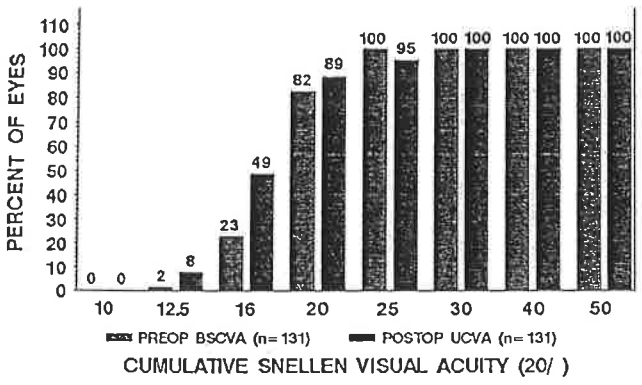

Figure 1. Preoperative BSCVA versus 6-month postoperative UCVA (BSCVA = best spectacle-corrected visual acuity; UCVA = uncorrected visual acuity).

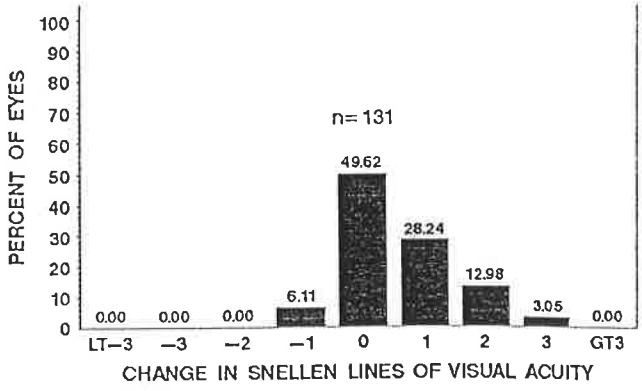

Figure 2. Change in BSCVA 6 months postoperatively.

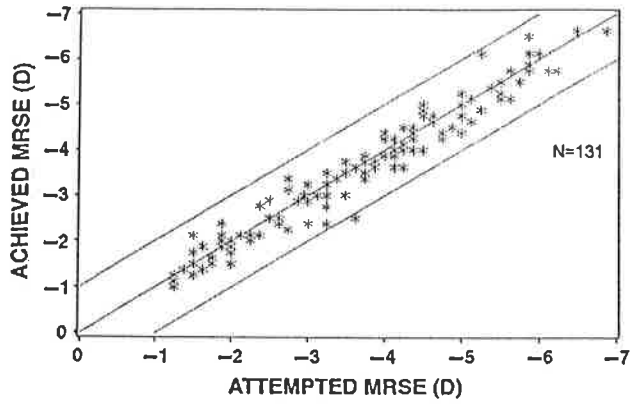

Figure 3. Attempted versus achieved MRSE refraction 6 months postoperatively shows a slight trend toward undercorrection (MRSE = mean refraction spherical equivalent).

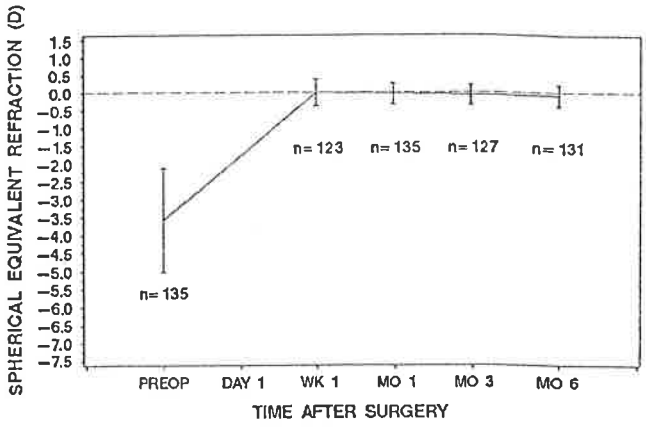

Figure 5. Change in MRSE from preoperatively to 6 months postoperatively.

($P<.05$) and in a direction that was beneficial to the patient. In the validation of this instrument, no definition of clinically significant changes for the individual subscales was provided; however, various effect sizes were provided as a guide to aid in the assessment of clinically significant changes. Using these effect sizes as guide, the improvements in driving and optical problems at the 3-month time point could be considered clinically significant (Table 5).

Complications

The only intraoperative complication was a buttonholed flap in the second eye of a patient who had previous treatment in the fellow eye. The patient was followed for 3 months and had PRK for myopic astigmatism outside this protocol.

The most common postoperative complication 1 month postoperatively or later was dry eye that required artificial tears (7 eyes [5.2%] at 1 month; 2 eyes [1.5%] at 6 months). A transient loss of 2 lines of BSCVA at 3 months in 2 eyes of 1 patient occurred due to eye dryness and eye tiredness. One eye developed grade 1 diffuse lamellar keratitis (DLK) that was treated with aggressive topical prednisolone phosphate 1%; the DLK resolved by the 1-week postoperative visit.

Two eyes of 2 patients required a secondary surgical intervention, 1 due to a peripheral hemorrhage in the lamellar bed that migrated over the pupil in the right eye. A flap refloat procedure was performed to remove the blood centrally; there was full recovery of visual acuity. Approximately 10 weeks after LASIK, the same patient presented with a corneal abrasion that occurred after the patient was poked in the eye with a branch while fighting a fire. By the 6-month postoperative visit, the cornea was clear except for a faint residual scar superiorly from the traumatic epithelial defect. The eye recovered uneventfully, gaining 1 line of BSCVA to 20/16.

The second patient had uneventful bilateral LASIK surgery but developed fine microstriae centrally in the right eye and reported central blurring of vision after surgery. The corneal flap was refloated to remove the striae. The eye recovered uneventfully by 6 months postoperatively without loss of BSCVA.

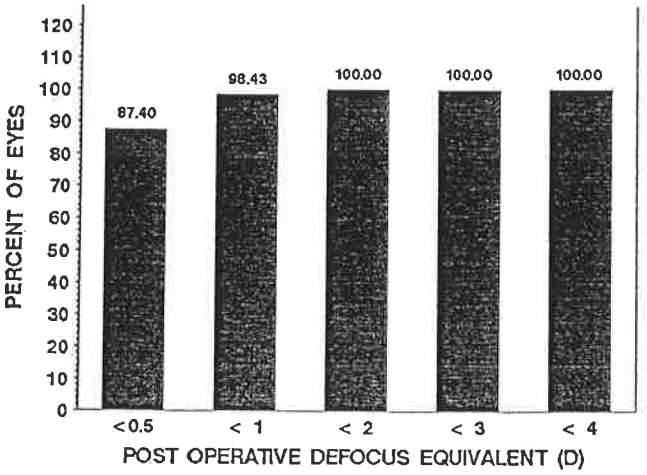

Figure 4. Defocus equivalent 6 months postoperatively.

DISCUSSION

In this study of LASIK for the treatment of low to moderate myopia with astigmatism using the EC-5000 CXII excimer laser with topographically guided CATz software, all refractive and visual acuity outcomes exceeded the FDA criteria 6 months postoperatively. No eye lost 2 or more lines of BSCVA 6 months after surgery, showing the safety of the procedure. Refractive stability was achieved 3 months after surgery.

Table 2. Photopic contrast sensitivity with and without glare.

Spatial Frequency	Eyes	Mean Contrast Sensitivity (Log Units) ± SD		Change in Mean (Log Units)	*P* Value* for Mean Change
		Preoperative	Postoperative		
1.5 cpd					
Glare	67	53.28 ± 20.35	54.31 ± 21.99	1.030	.7351
No glare	104	41.72 ± 18.06	43.58 ± 20.40	1.856	.2778
3.0 cpd					
Glare	67	76.46 ± 28.26	86.33 ± 31.65	9.866	.0177
No glare	104	74.47 ± 32.41	76.54 ± 29.81	2.067	.5233
6.0 cpd					
Glare	67	88.72 ± 42.08	106.1 ± 36.31	17.39	.0032
No glare	104	86.03 ± 40.55	92.23 ± 43.57	6.202	.1516
12.0 cpd					
Glare	67	48.75 ± 33.45	0.060 ± 0.24	4.761	.2031
No glare	104	45.35 ± 26.67	0.154 ± 0.363	−1.31	.6375
18.0 cpd					
Glare	67	19.94 ± 16.29	22.15 ± 15.20	2.209	.2576
No glare	104	19.10 ± 13.09	19.55 ± 13.26	0.452	.7326

cpd = cycles per degree
*$P < .05$, statistically significant

The results in this study are consistent with previous studies of topography-guided LASIK treatment of myopia with astigmatism, which found it to be safe and effective.[2,3] In 2 studies of CATz[2,3] with smaller sample sizes but a larger treatment range than in our study, no eye lost 2 or more lines of BSCVA. We also found no loss of BSCVA (Figure 2). Kermani et al.[3] found 90% of the eyes having the same procedure had an MRSE within ±0.50 D of the intended refraction, which is similar to our results (93% of eyes).

The apparent use of small OZs with CATz requires explanation. The OZ and TZ are misnomers when referring to these treatments because both zones combine to provide the refractive correction and should be referred to as the treatment zone. A small OZ might be more prone to decentration; however, we do not

Table 3. Changes in mesopic contrast sensitivity with and without glare.

Spatial Frequency	n	Mean Contrast Sensitivity (Log Units) ± SD		Change in Mean (Log Units)	*P* Value* for Mean Change
		Preoperative	Postoperative		
1.5 cpd					
Glare	67	40.03 ± 18.82	46.78 ± 16.90	6.746	.0249
No glare	104	46.70 ± 19.97	47.32 ± 22.34	0.615	.7688
3.0 cpd					
Glare	67	55.37 ± 28.74	63.37 ± 28.42	8.000	.0246
No glare	104	62.55 ± 30.38	63.87 ± 27.93	1.317	.6091
6.0 cpd					
Glare	67	51.82 ± 34.61	59.13 ± 36.18	7.313	.0723
No glare	104	58.21 ± 34.28	58.21 ± 32.51	0.000	1.0000
12.0 cpd					
Glare	67	19.09 ± 15.66	0.134 ± 0.344	0.746	.6215
No glare	104	20.67 ± 13.98	0.106 ± 0.309	−2.29	.0679
18.0 cpd					
Glare	67	6.25 ± 6.08	5.99 ± 7.21	−0.269	.7565
No glare	104	7.12 ± 7.10	5.67 ± 5.99	−1.44	.0325

cpd = cycles per degree
*$P < .05$, statistically significant

Table 4. Change in patient symptoms on a self-administered symptom questionnaire* 3 months after myopic LASIK.

	Percentage					
	Baseline		3 Mo Postop			
Question	None–Moderate	Marked–Severe	None–Moderate	Marked–Severe	Difference (Baseline Vs 3 Mo) in Marked–Severe†	*P* Value‡
Light sensitivity	95.28	4.72	98.36	1.64	−3.09	.1682
Difficulty night driving	76.98	23.02	100.0	0.00	−23.0	.0000
Difficulty reading	100.0	0.00	97.54	2.46	2.46	.0795
Double vision	100.0	0.00	100.0	0.00	0.00	—
Fluctuation in vision	100.0	0.00	100.0	0.00	0.00	—
Glare	97.66	2.34	100.0	0.00	−2.34	.0871
Halos	100.0	0.00	98.36	1.64	1.64	.1539
Star bursts	99.22	0.78	98.36	1.64	0.86	.5396
Dryness	100.0	0.00	96.72	3.28	3.28	.0420
Pain	100.0	0.00	100.0	0.00	0.00	—
Foreign body	100.0	0.00	100.0	0.00	0.00	—
Other§	94.59	5.41	97.14	2.86	−2.55	.5914

*Designed for study
†Negative value = decrease in severity of symptom from baseline; positive value = increase in severity of the symptom from baseline
‡$P < .05$, statistically significant
§Marked headaches at baseline (both eyes of 1 patient), mild headache (both eyes of 1 patient), marked "focusing" at 3 months (1 patient), and mild occasional pain at 3 months (left eye, 1 patient).

think that the risk for decentration with the customized aspherical TZ treatment is higher than that with the 6.5 mm OZ and 7.5 mm TZ commonly used in conventional treatments with the EC-5000 CXII in North America, especially since the procedure used a 200 Hz eye tracker.

The outcomes in this study confirm that topography-guided LASIK is a clinically valuable alternative to ocular wavefront-guided treatment of primary myopia and astigmatism. For example, within 6 months after surgery, 89% of eyes had a UCVA of 20/20 or better. In addition, at acuity levels of 20/16 or better, the 6-month postoperative UCVA exceeded the preoperative BSCVA in more than 25% of cases. There was a clinically significant gain of 2 lines or more of BSCVA in 16% of eyes. A study by Awwad et al.[17] treating a range of primary myopia similar to that in our study using the Visx CustomVue (Advanced Medical Optics) and CustomCornea (Alcon) wavefront platforms found that 89% of eyes had a UCVA of 20/20 or better. Similarly, a prospective randomized study of the WaveLight (WaveLight AG) and CustomCornea platforms found 80% of eyes achieved a UCVA of 20/20.[18] Comparison of our outcomes to results in these studies indicates that our topography-guided outcomes are equivalent to those reported for wavefront-guided treatments.

Although the outcomes in our study surpass the FDA criteria for approval, they can be improved with nomogram refinements. For example, the grouping of data points could be tighter in Figure 3 by incorporating changes in the laser's software to increase spherical or cylindrical laser values entered into the laser for treatment. In addition, nomogram adjustments at individual clinical sites could account for variations in temperature, humidity, and surgical technique.

Our study used an aspherical TZ to treat myopic astigmatism. Using aspherical treatments reduces the steep inflection changes in corneal curvature at the edge of the OZ. We found mild increases in total HOA RMS (0.04 μm), spherical aberration (0.053 μm), and coma (0.03 μm). After analyzing conventional ablations for myopia and myopic astigmatism with the EC-5000 CXII excimer laser, Du et al.[6] found an increase in the RMS value of 0.241 μm for total ocular HOAs, 0.139 μm for spherical aberration, and 0.183 μm for coma. The results of Du et al. show a substantial increase in HOAs compared with the values in our study. Du et al. also found a statistically significant increase in HOAs with conventional ablations compared with topography-guided aspherical treatments. The reduced induction of HOAs may increase visual quality.

There was a mean gain in photopic and mesopic contrast sensitivity with and without glare after LASIK in our study. Statistically significant gains in photopic and mesopic contrast sensitivity were seen at the low spatial frequencies (3 cpd and 6 cpd). There was a loss of mesopic contrast sensitivity at 18 cpd. Previous studies of LASIK using conventional

Table 5. Change in RSVP score after myopic LASIK.

Visit/Subscale	N Diff	Mean Base	Mean Score	Mean Diff*	P Value†	Effect Size
3 mo postop						
Concern	66	45.33	19.13	−26.20	.0000	−1.2654
Expectations	50	57.50	59.50	2.00	.6632	0.0859
Physical/social functioning	63	20.02	5.83	−14.19	.0000	−0.8615
Driving	60	21.88	8.89	−12.99	.0000	−0.6418
Symptoms	60	13.63	9.00	−4.63	.0319	−0.3074
Optical problems	60	10.65	3.94	−6.71	.0003	−0.5556
Glare	59	14.41	10.24	−4.17	.1040	−0.2977
Problem with corrective lenses	1	25.00	12.50	−12.50	.	.
Total score	66	21.26	5.36	−15.91	.0000	−1.2474
6 mo postop						
Concern	64	45.77	17.45	−28.32	.0000	−1.3500
Expectations	49	56.38	63.01	6.63	.1048	0.2801
Physical/social functioning	61	19.41	3.38	−16.03	.0000	−0.9898
Driving	58	21.62	7.76	−13.86	.0000	−0.6918
Symptoms	60	13.54	9.08	−4.46	.0337	−0.2957
Optical problems	61	9.57	3.36	−6.21	.0005	−0.5380
Glare	60	14.86	8.75	−6.11	.0148	−0.4423
Problem with corrective lenses	2	62.50	25.00	−37.50	.3743	.
Total Score	65	21.18	5.15	−16.03	.0000	−1.2418

Diff = difference
*Between baseline measurement and 3 months postoperatively
†$P < .05$, statistically significant

ablation[19–21] found a return to preoperative levels but did not find statistically significant increases in contrast sensitivity, as occurred in our study. Montés-Micó and Charman[21] report results of conventional LASIK using the EC-5000 laser for a similar treatment range and the FACT instrument to measure contrast sensitivity. They found that contrast sensitivity returned to preoperative levels by 6 months postoperatively and remained stable to 1 year.

To date, we do not believe there are any peer-reviewed reports of contrast sensitivity 6 months or more after CATz treatment. However, Hori-Komai et al.[14] report an increase in contrast sensitivity using aspherical algorithms (without treating the corneal irregularities) compared to conventional treatments with the Nidek laser. The increase in contrast sensitivity using CATz algorithm may be due to the combination of an aspherical algorithm and the removal of corneal irregularities. The aspherical algorithm uses a smooth TZ, which is configured to decrease the induced refractive power gradient between treated and nascent cornea and increase the effective OZ and, hence, increase visual quality in comparison with the conventional ablation profile.[14] Whether 1 component of the custom ablation algorithm has greater benefit than the other can be determined using a contralateral study design treating OATz in 1 eye and CATz in the other.

Studies using corneal wavefront treatments, aspheric algorithms, or ocular wavefront-guided treatments report decreases in contrast sensitivity or maintenance of contrast sensitivity at 6 months or more after LASIK.[22–24] Zhou et al.[22] treated up to −9.25 D of myopia and found a small reduction in mesopic contrast sensitivity with glare at high spatial frequencies 1 year after corneal wavefront-guided LASIK using the Esiris laser (Schwind Eye-Tech-Solutions GmbH). This is similar to our result of a reduction in mesopic contrast sensitivity at 18 cpd; however, Zhou et al. did not report an increase in contrast sensitivity postoperatively. Koller et al.[23] published results in 17 eyes that had LASIK with an aspherical algorithm using the WaveLight Eye-Q excimer laser; they found a mild loss in low-contrast visual acuity 1 month postoperatively. Jabbur and Kraff[24] report outcomes of ocular wavefront-guided LASIK using the WaveScan system for a treatment range similar to that in our study. They found that contrast sensitivity was preserved 6 months postoperatively. Based on these results, contrast sensitivity after LASIK with CATz is

equivalent to or better than results reported for conventional and wavefront-based LASIK.

In our study, visual symptoms after LASIK reported on subjective questionnaires were generally mild and less than those reported after standard ablation for myopia.[16] Compared with baseline, there was a 23% decrease in patients reporting marked to severe difficulties in night driving and no clinically significant increase in moderate to severe mesopic/scotopic symptoms such as halos, glare, or star burst postoperatively. Using the RSVP questionnaire in a mostly myopic population of patients (3% hyperopic) who had conventional excimer laser ablation, Schein et al.[16] found worsening of scotopic symptoms by an average of 14.5% and of driving by 29.5%, although it is unclear whether it was specifically night driving.

The increases in mesopic mean contrast percentage were statistically significant at 3 cpd and 6 cpd with glare, which were the same spatial frequencies and glare conditions that reached statistical significance under photopic conditions. This gain in contrast sensitivity with glare likely explains the improvement in night driving report in the current study. The results from both questionnaires clearly indicate that custom aspherical topography-guided LASIK gave excellent quality of vision outcomes and high patient satisfaction.

The 6-month results in this study indicate that topography-guided CATz treatment of myopic astigmatism with the EC-5000 CXII is safe, gives excellent refractive and visual acuity results, minimally increases HOAs, maintains or improves preoperative contrast sensitivity, and improves most patient symptoms compared with baseline.

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