Comparison of higher-order aberrations after wavefront-guided laser in situ keratomileusis and laser-assisted subepithelial keratectomy

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PURPOSE: To compare the higher-order aberrations (HOAs) in 70 eyes (38 patients) that had wavefront-guided laser in situ keratomileusis (LASIK) with those in 70 eyes (40 patients) that had wavefront-guided laser-assisted subepithelial keratectomy (LASEK) for the treatment of myopia.

SETTING: Department of Ophthalmology, Yonsei University College of Medicine, Myongdong Balgeun sesang Eye Clinic, and Seran Eye Center, Seoul, Korea.

METHODS: In a prospective study, 140 consecutive eyes of 78 patients were treated with wavefront-guided LASIK or LASEK according to the patient's choice after each procedure had been thoroughly explained. The patients were followed for 6 months. Best corrected visual acuity (BCVA), uncorrected visual acuity (UCVA), manifest refraction, and wavefront aberrations were measured at baseline and 1, 3, and 6 months after surgery.

RESULTS: There were no significant differences in postoperative BCVA, UCVA, and manifest refraction between groups. The mean root-mean-square wavefront error of HOAs for a scotopic pupil in the wavefront-guided LASIK group was significantly smaller than that in the wavefront-guided LASEK group at 1 month. Analyzing individual Zernike coefficients, the spherical aberration and second coma were significantly smaller in the wavefront-guided LASIK group than in the wavefront-guided LASEK group at 1 month. This difference in HOAs between groups disappeared at 3 and 6 months.

CONCLUSIONS: The HOAs in the scotopic condition were not different between the wavefront-guided LASIK and LASEK groups beginning 3 months after surgery. However, the HOAs in the LASIK and LASEK groups had a different time course, especially in the case of spherical aberration. This finding suggests that postoperative changes in aberration contribute to the final outcome of wavefront-guided ablation.

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It has been suggested that wavefront-guided laser refractive surgery reduces the higher-order aberrations (HOAs) that cause glare, halo, and disturbance in night vision.[1–3] Theoretically, customized ablation would lead to accurate correction of the monochromatic aberrations of the eye and reduction of these symptoms.

However, the cornea is a living optical surface with biomechanical properties that are affected by the surgery—the flap formation, removal of tissue in excimer laser procedures, and the healing effect that occurs after treatment.[4] Laser in situ keratomileusis (LASIK) and laser-assisted subepithelial keratectomy (LASEK) procedures are supposed to produce different clinical results after wavefront-guided laser refractive surgery. Some authors insist that flap formation during LASIK can modify the eye's existing natural HOAs,[5] whereas others propose that the laser ablation rather than the microkeratome cut induces HOAs during LASIK surgery.[6] In contrast, surface ablations such as LASEK and photorefractive keratectomy (PRK) are thought to promote more postoperative wound remodeling. Such biomechanical changes can have an impact on the ultimate corneal asphericity and possibly the HOAs, including spherical aberration.[7]

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To our knowledge, there has been no comparison of visual outcome and changes in optical quality of cornea between wavefront-guided LASIK and LASEK. We conducted the current prospective study to compare the amount of HOAs of the cornea after wavefront-guided LASIK and wavefront-guided LASEK for the management of myopia.

PATIENTS AND METHODS

Seventy-eight patients with a manifest refraction from −0.80 to −6.60 D were enrolled in this study between September 2002 and July 2003. Wavefront-guided LASIK was performed in 70 eyes of 38 patients and wavefront-guided LASEK in 70 eyes of 40 patients. Patients with diabetes mellitus, connective tissue disease, amblyopia, corneal disease, cataract, glaucoma, or retinal disease were excluded. All patients received full explanations about the procedures, including the potential advantages, disadvantages, and complications, and each patient was then allowed to select a procedure. Informed consent was obtained before surgery in all cases in accordance with the World Medical Association Declaration of Helsinki. The patients were followed for 6 months.

Wavefront Sensing and Ablation Profile Evaluation

The preoperative ophthalmic examinations in all patients included slitlamp microscopy, fundus examination, cycloplegic and manifest refractions, corneal keratometry, corneal topography, corneal pachymetry, and Goldmann tonometry. Pupil diameter was measured under photopic and scotopic illumination using a Rosenbaum near-card scale. All HOAs were measured by Wavescan (Visx Inc.) using a Hartmann-Shack sensor in the natural scotopic condition after 10-minute dark adaptation. The values of HOAs were presented as root-mean-square (RMS, in micrometers) in Belle aberration maps, which displayed HOAs only after sphere and cylinder had been removed. All RMS values were obtained from 6.0 mm pupil measurement in the natural scotopic condition. Data from Wavescan were transferred by floppy disk to the excimer laser system (Star S4, Visx Inc.). Besides spherical and cylindrical elements, HOAs in the 3rd, 4th, 5th, and 6th orders were corrected as determined by Wavescan. For HOAs, no physician adjustment was used for the CustomCornea.

Laser In Situ Keratomileusis Procedure

The procedure was performed under topical anesthesia with 3 drops of proparacaine hydrochloride 0.5% (Alcaine) over a 10-minute interval (every 5 minutes). A rigid eyelid speculum was used. One radial mark at the 8-o'clock position was made with a marker pen (Accu-line, Katena Products, Inc.). A Hansatome microkeratome (Bausch & Lomb Surgical) was used to create a flap of 160 μm. The flap was raised using a spatula, and the stromal bed was exposed. Information from Wavescan, translated into a treatment plan and copied to a floppy disk, was transferred into the Star S4 excimer laser system. The laser was fired on a dried corneal surface with the following operative parameters: emission wavelength 193 nm, energy fluence 160 mJ/cm^2, repetition rate 10 Hz, and ablation zone 8.00 mm with no blend zone. The optical zone varied from 6.0 mm to 7.3 mm depending on the pupil size. The eye tracker was automatically on during laser ablation. Afterward, the flap was replaced using a spatula with the correspondence of the peripheral epithelial markings. The epithelial and stromal portions of the flap were then irrigated with a cannula. At the end of the procedure, ofloxacin 0.3% (Ofloxacine) was instilled into the treated eye. One drop of ofloxacine and 1 of fluorometholone 0.1% (Ocumetholon) were prescribed 4 times daily for the first postoperative week and twice daily for the second week.

Laser-Assisted Subepithelial Keratectomy Procedure

Anesthesia was achieved with 3 drops of Alcaine over a 10-minute interval (every 5 minutes). A speculum was applied to the patient's eye, an alcohol solution cone (J2905, Janach) with a diameter of 8.5 mm was placed on the eye, and 0.3 mL ethyl alcohol 20% was instilled inside the cone and left for about 30 seconds and then washed off carefully with balanced salt solution (BSS) so the epithelium around the flap was not disturbed. The epithelial flap was gently lifted with an epithelial micro-hoe (J 2915A, Janach) and then peeled back as a single sheet toward the 12-o'clock position using a spatula (J2910A, Janach). Wavefront-guided excimer laser treatment was performed in the usual manner using the same nomogram and laser system as in wavefront-guided LASIK with an eye-tracking device. The flap was washed with a BSS and then repositioned carefully with a spatula. The operation was finished when the therapeutic soft contact lens was placed on the operated eye. One drop of Ofloxacine and Ocumetholon was prescribed 4 times daily for the first postoperative month, 2 times daily for the second month, and once a day for the third month.

Statistical Analysis

Independent *t* tests were used to compare the preoperative pupil size, preoperative and postoperative visual acuities, mean spherical equivalent (SE) refractions, RMS values of HOAs, and mean changes in HOAs between groups. Multivariate tests using the general linear model were used to compare RMS values of HOAs within both groups of eyes according to the time course. Individual Zernike coefficients obtained from WaveScan were compared between groups as well as preoperatively and postoperatively. Comparisons of Zernike coefficients were made

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using the independent *t* test with Bonferroni correction to eliminate statistically significant findings resulting from chance. A *P* value less than 0.05 was considered significant.

RESULTS

There were no between-group differences in preoperative and postoperative refractions and visual acuities (Tables 1 and 2). At baseline, the mean RMS error of HOAs was 0.29 ± 0.11 in the wavefront-guided LASIK group and 0.28 ± 0.09 in the wavefront-guided LASEK group (Table 3). There was no statistically significant difference between groups (*P* = .378) (Table 3). The mean baseline pupil sizes in photopic and scotopic conditions were 3.79 ± 0.51 mm and 7.03 ± 0.55 mm, respectively, in the wavefront-guided LASIK group, and 3.69 ± 0.71 mm and 7.01 ± 0.58 mm, respectively, in the wavefront-guided LASEK group. The between-group difference in pupil size was not statistically significant (*P* = .47 and *P* = .51, respectively).

At 1, 3, and 6 months, there were no between-group differences in the uncorrected visual acuity (UCVA) and postoperative SE refractions (Tables 1 and 2). However, the mean HOA was significantly smaller in the wavefront-guided LASIK group (0.28 ± 0.11) than in the wavefront-guided LASEK group (0.34 ± 0.11) (*P* = .0003) at 1 month (Table 3, Figure 1). The difference in HOAs between groups disappeared at 3 and 6 months (Table 3, Figure 1). The mean changes in HOAs from preoperative levels at 1 month were also significantly smaller in the wavefront-guided LASIK group than in the wavefront-guided LASEK group (Table 4). The mean HOA was significantly increased at 1 month and remained at a similar level at 3 months in the wavefront-guided LASEK group (Figure 1). The mean HOA was not altered from baseline at 1 month in the wavefront-guided LASIK group but was significantly increased at 3 months (Figure 1).

With Bonferroni correction, individual Zernike coefficients were significantly different between groups in terms of spherical aberration (*P* = .003) and second coma (*P* = .002) at 1 month (Table 5, Figure 2). From 3 months after surgery, there were no significant between-group differences in spherical aberration and second coma (Table 5, Figure 2). The mean changes in spherical aberration from preoperative levels at 1 month were also significantly smaller in the wavefront-guided LASIK group than in the wavefront-guided LASEK group (Table 6). Spherical aberration was significantly increased from baseline at 1 month in the wavefront-guided LASEK group (Figure 2). However, spherical aberration was significantly increased at 3 months with respect to the 1-month level in the wavefront-guided LASIK group (Figure 2).

Table 1. Mean SE at baseline and 1, 3, and 6 months after surgery.

Measurement Time	SE (D) WF LASIK (n = 70)	SE (D) WF LASEK (n = 70)	*P* Value*
Preoperative	−3.52 ± 1.13	−3.33 ± 0.57	.169
Postoperative			
1 month	−0.20 ± 0.32	−0.30 ± 0.42	.102
3 months	−0.21 ± 0.36	−0.30 ± 0.36	.154
6 months	−0.23 ± 0.37	−0.35 ± 0.26	.090

SE = spherical equivalent; WF = wavefront guided.
*Independent *t* test

Table 2. Mean UCVA and BCVA at baseline and 1, 3, and 6 months after surgery.

Measurement Time	UCVA and BCVA WF LASIK (n = 70)	UCVA and BCVA WF LASEK (n = 70)	*P* Value*
Preoperative BCVA	1.00 ± 0.02	1.00 ± 0.03	.832
Postoperative UCVA			
1 month	0.99 ± 0.06	0.96 ± 0.10	.051
3 months	0.99 ± 0.05	0.97 ± 0.07	.073
6 months	1.01 ± 0.05	0.99 ± 0.08	.186

BCVA = best-corrected visual acuity; UCVA = uncorrected visual acuity; WF = wavefront guided
*Independent *t* test

DISCUSSION

Our data demonstrate the different time course of changes in HOAs between wavefront-guided LASIK and wavefront-guided LASEK groups after surgery. We are aware of no published reports that compare HOAs between these groups. Corneal response to LASIK surgery such as the flap formation, biomechanical changes, and postoperative epithelial thickening may significantly induce

Table 3. Mean total HOAs at baseline and 1, 3, and 6 months after surgery.

Measurement Time	RMS WF LASIK (n = 70)	RMS WF LASEK (n = 70)	*P* Value*
Preoperative	0.29 ± 0.11	0.28 ± 0.09	.378
Postoperative			
1 month	0.28 ± 0.11	0.34 ± 0.11	.0003†
3 months	0.31 ± 0.10	0.32 ± 0.09	.404
6 months	0.31 ± 0.11	0.33 ± 0.06	.277

HOAs = higher-order aberrations; RMS = root mean square of Belle aberration maps; WF = wavefront guided
*Independent *t* test
†Statistically significant ($P < .05$)

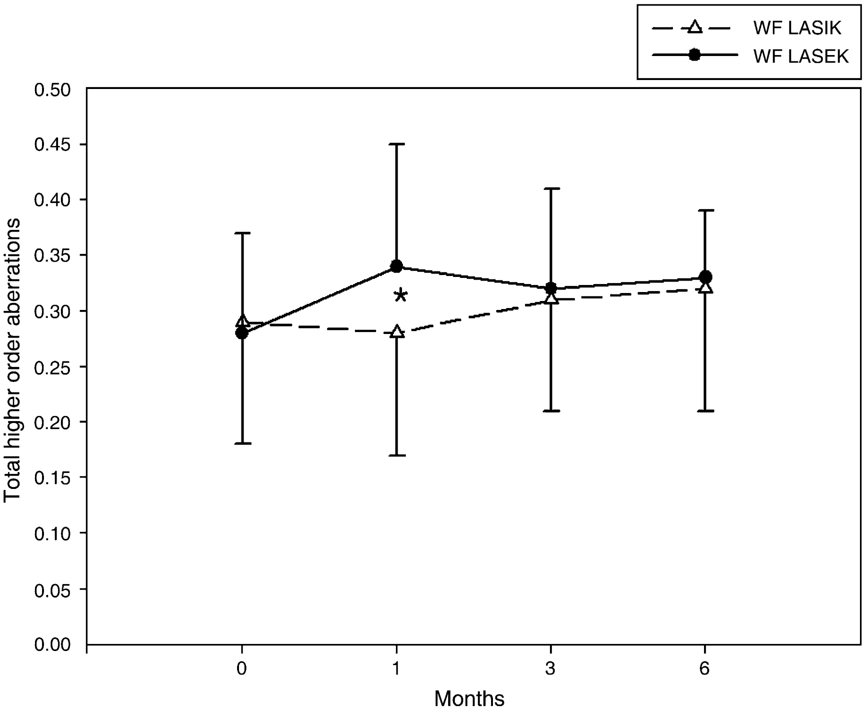

Figure 1. (Chung) The time course of changes in total HOAs (RMS) after wavefront-guided LASIK and wavefront-guided LASEK. There was a statistically significant difference between groups at 1 month (*) (P = .0003).

HOAs and affect visual outcomes.[8] Previous studies report that the keratome incision results in modification of the eye's existing natural HOAs. In contrast, LASEK is thought to promote more postoperative wound remodeling than LASIK, which can affect HOAs, including spherical aberration.[7] Our results demonstrate that the mean HOA induced by surgery itself was smaller in the wavefront-guided LASIK group than in the wavefront-guided LASEK group at 1 month, which means that the contribution of flap formation to HOAs is relatively less than the aberrations induced by surgery itself or epithelial wound healing in the LASEK group.

Higher-order aberrations after surgery show dynamic changes, especially in terms of spherical aberration. Several studies report elevated levels of spherical aberration after conventional PRK or LASIK.[9–11] To eliminate all the significant aberrations of the eye, the customized ablation was designed.[12] However, our data show that spherical aberration was increased from 3 months after customized ablation in the wavefront-guided LASIK group, and this increase was statistically significant in the wavefront-guided LASEK group. This finding implies that spherical aberration is still 1 of the most important HOAs after wavefront-guided refractive surgery. When examined more closely, at 1 month, spherical aberration was significantly smaller in the wavefront-guided LASIK group than in the wavefront-guided LASEK group. This suggests that the different postoperative corneal responses caused the discrepancy in HOAs between procedures, primarily in terms of postoperative changes in the amount of spherical aberration. Even the most precise ablation for aberration-free cornea could not achieve the aberration-free refractive outcome because of changes in HOAs during the postoperative period.

Table 4. Mean changes in total HOAs 1, 3, and 6 months after surgery.

	RMS Changes from Baseline		
Postoperative Time	WF LASIK (n = 70)	WF LASEK (n = 70)	*P* Value*
1 month	−0.01 ± 0.02 (−0.31 to 0.41)	0.06 ± 0.13 (−0.27 to 0.38)	.0002†
3 months	0.02 ± 0.17 (−0.39 to 0.40)	0.05 ± 0.11 (−0.36 to 0.39)	.199
6 months	0.03 ± 0.12 (−0.27 to 0.33)	0.05 ± 0.09 (−0.30 to 0.33)	.082

HOA = higher-order aberration; RMS = root-mean-square of Belle aberration maps; WF = wavefront guided
*Independent *t* test
†Statistically significant ($P < .05$)

Table 5. Mean individual Zernike coefficients in each group at baseline and 1, 3, and 6 months after surgery.

Zernike Coefficient	Before Surgery (n = 70)	After Surgery		
		1 Month (n = 70)	3 Months (n = 70)	6 Months (n = 70)
Z_3^1 (coma)				
WF LASIK	0.16 ± 0.10	0.15 ± 0.10	0.18 ± 0.12	0.18 ± 0.09
WF LASEK	0.16 ± 0.08	0.19 ± 0.10	0.18 ± 0.10	0.19 ± 0.08
Z_3^3 (trefoil)				
WF LASIK	0.14 ± 0.06	0.11 ± 0.07	0.14 ± 0.12	0.13 ± 0.08
WF LASEK	0.14 ± 0.08	0.14 ± 0.07	0.12 ± 0.06	0.12 ± 0.08
Z_4^0 (spherical aberration)				
WF LASIK	0.05 ± 0.09	0.04 ± 0.11*	0.09 ± 0.11	0.09 ± 0.11
WF LASEK	0.03 ± 0.08	0.09 ± 0.11*	0.11 ± 0.10	0.11 ± 0.10
Z_4^2 (2nd astigmatism)				
WF LASIK	0.06 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.08 ± 0.04
WF LASEK	0.05 ± 0.04	0.09 ± 0.06	0.08 ± 0.11	0.09 ± 0.12
Z_4^4 (quadrafoil)				
WF LASIK	0.07 ± 0.07	0.07 ± 0.04	0.07 ± 0.04	0.08 ± 0.05
WF LASEK	0.06 ± 0.04	0.07 ± 0.04	0.06 ± 0.04	0.07 ± 0.03
Z_5^1 (second coma)				
WF LASIK	0.04 ± 0.03	0.04 ± 0.03*	0.05 ± 0.04	0.05 ± 0.03
WF LASEK	0.04 ± 0.02	0.06 ± 0.04*	0.05 ± 0.03	0.05 ± 0.03

WF = wavefront guided
*A statistically significant difference was found ($P < .004$; independent *t* test with Bonferroni correction)

Visual acuity and refractive outcome after wavefront-guided LASIK and LASEK were excellent. There were no significant between-group differences at any postoperative point; however, on average, wavefront-guided LASEK patients' visual performance fluctuated more than that of wavefront-guided LASIK patients. Kaya et al.[13] report that both standard LASIK and LASEK are effective for treatment of myopia less than −6.00 D and offer refractive stability at 6 months. In another study, 6/6 UCVA rate in the standard LASEK group for treatment of myopia less than −6.00 D was higher than that in the standard LASIK group at 3 months because of flap-induced aberration (P. L. Condon, MD, "LASEK Versus LASIK for Low Myopia," presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Francisco, California, USA, April 2003). However, in our study, visual acuity and HOAs did not differ between groups 3 and 6 months after customized ablation. Therefore, from the point of view of final visual acuity and

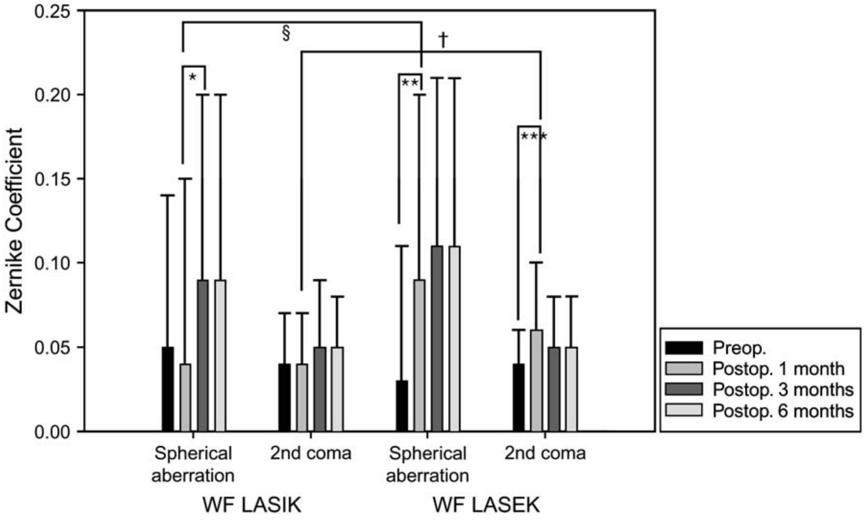

Figure 2. (Chung) Comparison of two Zernike coefficients values (spherical aberration, second coma) in preoperative and postoperative higher-order aberrations with Bonferroni correction. There was a statistically significant difference in spherical aberration between postoperative 1 and 3 months in the wavefront-guided LASIK group (*) and in spherical aberration and second coma between preoperative and postoperative 1 month in the wavefront-guided LASEK group (**, ***). At 1 month, there was a statistically significant difference in spherical aberration and second coma between groups (§,†; $P < .004$).

Table 6. Mean changes in spherical aberration (Z_4^0) 1, 3, and 6 months after surgery.

Postoperative Time	Spherical Aberration Changes from Baseline		
	WF LASIK (n = 70)	WF LASEK (n = 70)	*P* Value*
1 month	−0.01 ± 0.10 (−0.41 to 0.39)	0.06 ± 0.12 (−0.20 to 0.34)	.00004†
3 months	0.04 ± 0.11 (−0.48 to 0.28)	0.08 ± 0.13 (−0.14 to 0.41)	.012
6 months	0.04 ± 0.12 (−0.23 to 0.47)	0.09 ± 0.12 (−0.14 to 0.36)	.026

WF = wavefront guided
*Independent *t* test with Bonferroni correction
†Statistically significant ($P < .004$)

HOAs, even if wavefront-guided LASEK patients' visual performance fluctuated more than that of wavefront-guided LASIK patients, we think wavefront-guided LASEK is equally effective for customized ablation considering the surgeon factor that may arise during LASIK flap formation.

The results of this study indicate that both wavefront-guided LASIK and wavefront-guided LASEK are effective for customized ablation. However, only with the development of new technologies considering postoperative changes of HOAs, especially spherical aberration, can aberration-free refractive corrections be expected.

REFERENCES

1. McDonald MB. Summit-Autonomous Custom Cornea laser in situ keratomileusis outcomes. J Refract Surg 2000; 16:S617–S618
2. Panagopoulou SI, Pallikaris IG. Wavefront customized ablations with the WASCA Asclepion workstation. J Refract Surg 2001; 17:S608–S612
3. Kanjani N, Jacob S, Agarwal S, et al. Wavefront- and topography-guided ablation in myopic eyes using Zyoptix. J Cataract Refract Surg 2004; 30:398–402
4. Schwiegerling J, Snyder RW, Lee JH. Wavefront and topography: keratome-induced corneal changes demonstrate that both are needed for custom ablation. J Refract Surg 2002; 18:584–588
5. Pallikaris IG, Kymionis GD, Panagopoulou SI, et al. Induced optical aberrations following formation of a laser in situ keratomileusis flap. J Cataract Refract Surg 2002; 28:1737–1741
6. Hersh PS, Fry K, Blaker JW. Spherical aberration after laser in situ keratomileusis and photorefractive keratectomy: clinical results and theoretical models of etiology. J Cataract Refract Surg 2003; 29:2096–2104
7. Mrochen M, Donitzky C, Wüllner C, Löffler J. Wavefront-optimized ablation profiles: theoretical background. J Cataract Refract Surg 2004; 30:775–785
8. Oshika T, Klyce SD, Applegate RA, et al. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. Am J Ophthalmol 1999; 127:1–7
9. Oliver KM, Hemenger RP, Corbett MC, et al. Corneal optical aberrations induced by photorefractive keratectomy. J Refract Surg 1997; 13:246–254
10. Schwiegerling J, Snyder RW. Corneal ablation patterns to correct for spherical aberration in photorefractive keratectomy. J Cataract Refract Surg 2000; 26:214–221
11. Moreno-Barriuso E, Merayo Lloves J, Marcos S, et al. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. Invest Ophthalmol Vis Sci 2001; 42:1396–1403
12. MacRae SM, Krueger RR, Applegate RA. Customized Corneal Ablation: The Quest for SuperVision. Thorofare, NJ, Slack, 2001
13. Kaya V, Oncel B, Sivrikaya H, Yilmaz OF. Prospective, paired comparison of laser in situ keratomileusis and laser epithelial keratomileusis for myopia less than −6.00 diopters. J Refract Surg 2004; 20:223–228