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Analysis of Corneal Higher-order Aberrations after Myopic Refractive Surgery

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This study was performed to analyze the optical aberrations of the cornea induced by myopic refractive surgery. Corneal total higher-order aberrations, spherical aberration and coma for 4-mm and 6-mm pupils were measured using a wave-front analyzer. The amount of aberrations of the oblate corneal optics by the achieved correction was found to be larger than for the prolate corneal shape with complete eye, in an emmetropia control group. The change in corneal shape acts as an optical factor that degrades the quality of the retinal image; it seems to be one of the important factors related to quality of vision.

Keywords : Corneal refractive surgery, Corneal higher order aberrations, Spherical aberration
OCIS codes : (330.3350) Vision-laser damage; (080.1005) Aberration expansions

I. INTRODUCTION

Among the methods of correcting refractive errors of the eye, excimer laser surgery is considered to be the most effective. With the development of new generations of excimer lasers, nowadays corneal refractive surgery is used as a means for correcting not only lower-order aberration with spherical and astigmatic refractive errors, but also higher-order aberrations (HOAs) with wave-front errors [1]. Furthermore, the new aberrometer in wave-front technology explores how the HOAs affect visual performance, and provides a better understanding of our visual system [2-4].

The principles of myopic refractive surgery are to correct the refractive error of the eye by flattening the radius of curvature of the central cornea, which accounts for more than 70% of the optical refractive power of the eye. Ocular aberrations linked by various HOAs in optical systems are known to cause defects in retinal image quality [5]. The amount of HOAs, including spherical aberration (SA) and coma aberration, is increased by changing from a prolate to an oblate corneal shape after refractive surgery [6, 7]. Those shape changes in the cornea may affect corneal asphericity, and especially SA. In addition, HOAs are highly affected by increased pupil size [8]. The HOA response of the cornea, according to the degree of ablation, in myopic refractive-surgery patients should be reflected in our understanding of visual quality after corneal refractive surgery such as LASIK or LASEK.

The purpose of this study was to analyze corneal HOAs induced by myopic refractive surgery in patients undergoing laser *in situ* keratomileusis (LASIK) or laser-assisted sub-epithelial keratectomy (LASEK), and to investigate the effect of ablation profiles on corneal wave-front errors.

II. METHODS

Subjects for this study were 120 eyes that had undergone conventional myopic LASIK or LASEK, for 6 months or more after surgery, and 40 eyes of 20 emmetropes as a control group. The subjects who met the criterion of best unaided monocular visual acuity of 0.9 (including -0.25D to +0.75D of spherical refractive errors, and no more than 0.50D of astigmatic refractive errors) or better in both groups were selected for this study.

120 eyes were divided into three groups, based on spherical equivalent (SE) of the achieved correction: the low-myopia group (SE < -3.00 D), moderate-myopia group (-3.00 ≤ SE < -6.00 D), and high-myopia group (SE ≥ -6.00 D).

This study was approved by the Institutional Review Board (IRB) of Eulji University. Written informed consent was obtained from the subjects participating in the study,

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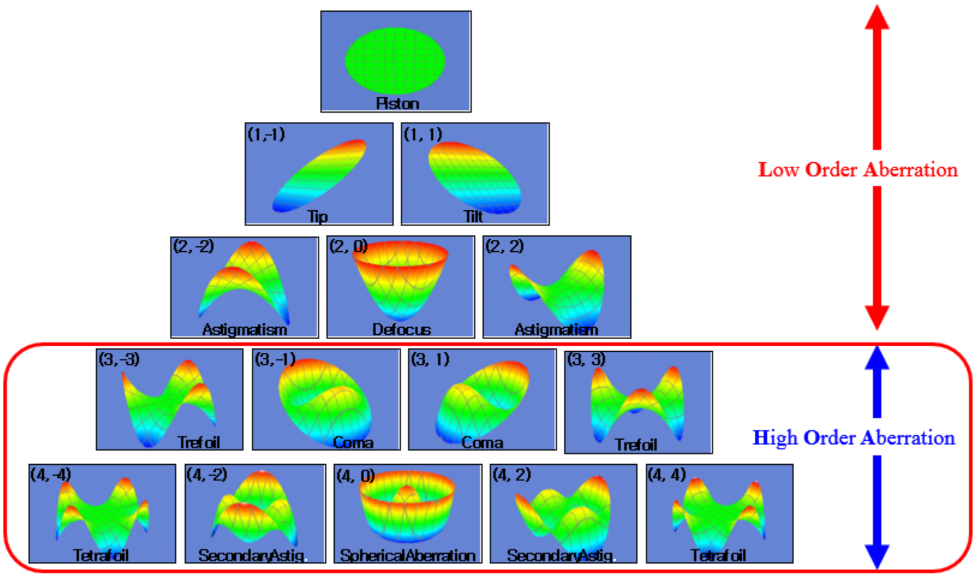


FIG. 1. Terms of the Zernike polynomial, organized as a pyramid, showing lower- and higher-order aberrations.

following a detailed explanation of the study's procedures.

The wave-front analysis was performed using a Wave-front Analyzer (KR-1W, Topcon, Japan) with the Hartmann-Shack technique. Corneal HOAs for 4-mm and 6-mm pupils analyzed total HOAs, coma included in third-order aberrations, and SA included in fourth-order aberrations (Fig. 1). Corneal total HOAs were calculated as the root-mean-square (RMS) of the third- and fourth-order Zernike coefficients. To maximize the influence of pupil size, wave-front aberrations were measured in mesopic lighting conditions.

Corneal asphericity (*Q* value) was taken by Pentacam Oculyzer topography (Oculus Inc., Germany) with a rotating Schiempflug camera.

The SPSS/window program (version 21.0, SPSS, Chicago, IL) was used for statistical analysis throughout this study, and graphs were produced using the Origin 8.0 program (OriginLab Co., Northampton, USA). Normality of data was investigated with the Kolmogorov-Smirnov test. For RMS values of corneal HOAs, differences between data were evaluated by analysis of variance (ANOVA) for comparison of the three groups. The results were expressed as mean and standard deviation (SD). Correlation coefficients were established by Pearson correlation. Difference was considered statistically significant when the *p* value was less than 0.05.

III. RESULTS AND DISCUSSION

60 subjects (120 eyes) who had undergone conventional myopic LASIK or LASEK, plus 20 emmetropes (40 eyes) as a control group, participated in this study. The mean age of the subjects in the post-refractive-surgery group was 23.17 ± 2.25 years, and the period after refractive surgery was 20.15 ± 12.45 months. The mean age of the emmetropia subjects was 22.50 ± 1.74 years. The data for the subjects are outlined in Tables 1 and 2.

Corneal aberrations of total HOA, SA, and coma for 4-mm and 6-mm pupils are compared in Fig. 2. For a 4-mm pupil size, in the myopic refractive-surgery group the RMS values of total HOA, SA, and coma were 0.182 ± 0.071, 0.081 ± 0.040, and 0.119 ± 0.061 μm respectively. In emmetropic eyes with corneal aberrations, total HOA, SA, and coma were 0.143 ± 0.054, 0.047 ± 0.024, and 0.088 ± 0.046 μm respectively. There were statistically significant differences in total HOA, SA, and coma for a 4-mm pupil between the emmetropia and myopic refractive-surgery groups ($p = 0.000$, $p = 0.000$ and $p = 0.001$ respectively). On the other hand, for a 6-mm pupil size, in the myopic refractive-surgery group the RMS values of total HOA, SA,

TABLE 1. Demographics and clinical data of study subjects

Parameters	Post-op group	Emmetropes
Number of eyes (n)	120	40
Age (years)	23.17 ± 2.25[1)]	22.50 ± 1.74
Sex (M, F)	42, 78	22, 18
UCDVA (LogMAR)	-0.025 ± 0.06	-0.032 ± 0.05
Mean *K* (D)	38.82 ± 1.59	42.84 ± 0.92
Corneal thickness (μm)	471.6 ± 30.97	549.5 ± 30.87
Q value (6-mm zone)	0.79 ± 0.40	-0.34 ± 0.12
Mesopic pupil size (mm)	6.56 ± 0.55	6.50 ± 0.55

Post-op, postoperative group; [1)], Mean ± standard deviation; UCDVA, uncorrected distance visual acuity; LogMAR, Log of the minimum angle of resolution; *K*, keratometry value; *Q* value, corneal asphericity.

TABLE 2. Characteristics of myopic refractive-surgery group

Parameters	Post-op group
Number of eyes (*n*)	120
Type of refractive surgery; LASIK, LASEK	38% (n = 46), 62% (n = 74)
Optical zone (mm) (range)	6.39 ± 0.22[1)] (5.80 to 6.70)
Ablation depth (μm) (range)	85.24 ± 22.58 (38 to 139)
Duration of post-op (months) (range)	20.15 ± 12.45 (6 to 48)
Sphere of correction (D) (range)	-4.63 ± 1.68 (-0.25 to -8.50)
Cylinder of correction (D) (range)	-1.14 ± 0.80 (0.00 to -3.50)
SE of correction (D) (range)	-5.20 ± 1.68 (-1.25 to -9.00)
Grouping into SE of correction (D)	
Low Myopia (<-3.00) / SE (D) (range)	13% (n = 16) / -2.55 ± 0.55 (-1.25 to -2.98)
Moderate Myopia (-3 to -6.00) / SE (D)	56% (n = 67) / -4.76 ± 0.72 (-3.31 to -5.88)
High Myopia (≥-6.00) / SE (D) (range)	31% (n = 37) / -7.13 ± 0.96 (-6.00 to -9.00)

Post-op, postoperative group; [1)], Mean±standard deviation; SE, spherical equivalent.

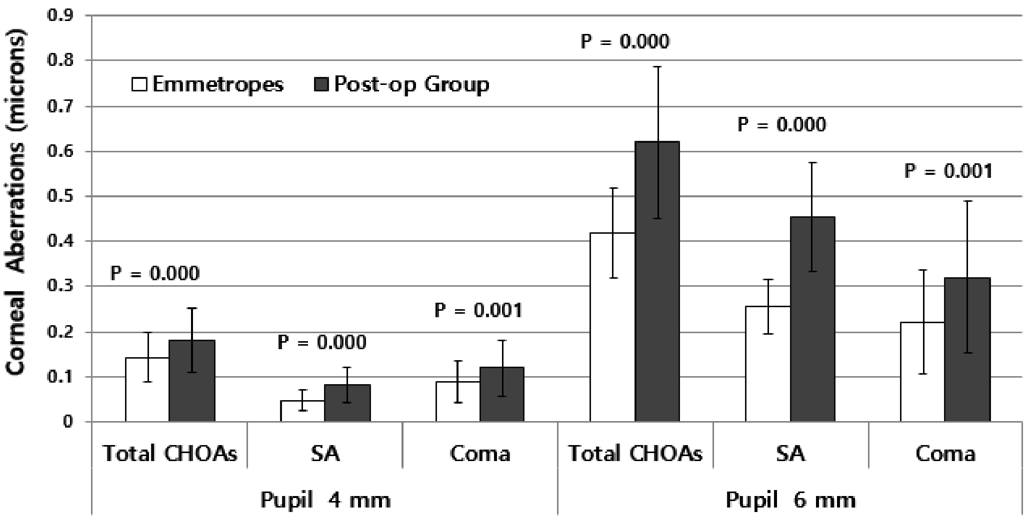


FIG. 2. Comparison of corneal higher-order aberrations (CHOAs) for 4-mm and 6-mm natural pupils, between emmetropic and myopic refractive-surgery groups.

and coma were 0.620 ± 0.168, 0.454 ± 0.121, and 0.320 ± 0.168 μm respectively. For emmetropic eyes the RMS values of total HOA, SA, and coma were 0.419 ± 0.099, 0.255 ± 0.061, and 0.221 ± 0.116 μm respectively. There were statistically significant differences in total HOA, SA, and coma for a 6-mm pupil with corneal aberrations between the two groups ($p = 0.000$, $p = 0.000$, and $p = 0.001$ respectively).

The magnitudes of the induced corneal aberrations for a 6-mm pupil size in the myopic refractive-surgery group were generally greater than those in the control group. It is clear that there are more corneal aberrations with increasing pupil size.

As mentioned, the myopic refractive-surgery group was divided into three groups based on spherical equivalent (SE) of the achieved correction, to evaluate corneal HOAs according to ablation depth: the low-myopia group ($SE < -3.00$ D), moderate-myopia group ($-3.00 \leq SE < -6.00$ D) and high-myopia group ($SE \geq -6.00$ D). Corneal aberrations including total CHOA, SA, and coma are summarized by refractive status in Table 3.

For 4-mm and 6-mm pupil sizes, although the amount of total HOAs, SA, and coma increases as myopia progresses, there was no significant difference in total HOA, SA, and coma with corneal aberrations after treatment, for low myopia and moderate myopia. However, this study found that there were significant differences in total HOAs and SA between the low- and high-myopia groups, as well as between the moderate- and high-myopia groups.

In the present study, the results suggest that excimer-laser surgery induces a large amount of corneal SA compared to emmetropes, especially in treatment for high myopia. In fact, quite a number of myopic eyes experience increased SA due to conventional LASIK or LASEK [9].

TABLE 3. The mean corneal higher-order aberrations for 4-mm and 6-mm pupil sizes, in the emmetropic group and the three myopic refractive surgery-groups, classified by spherical equivalent (SE) of the achieved correction

Groups	Corneal aberrations (4-mm pupil)		
	Total CHOA RMS (μm)	SA (μm)	Coma (μm)
Low Myopia (*n* = 16)	0.167 ± 0.064[a]	0.072 ± 0.038[a]	0.110 ± 0.055
Moderate Myopia (*n* = 67)	0.191 ± 0.092[a]	0.076 ± 0.029[a]	0.126 ± 0.066
High Myopia (*n* = 37)	0.203 ± 0.068[b]	0.099 ± 0.040[b]	0.134 ± 0.065
p value	0.037*	0.003*	0.112
Emmetropes (*n* = 40)	0.142 ± 0.053	0.047 ± 0.024	0.087 ± 0.046
Groups	Corneal aberrations (6-mm pupil)		
	Total CHOA RMS (μm)	SA (μm)	Coma (μm)
Low Myopia (*n* = 16)	0.575 ± 0.101[a]	0.418 ± 0.083[a]	0.299 ± 0.167
Moderate Myopia (*n* = 67)	0.579 ± 0.153[a]	0.420 ± 0.107[a]	0.304 ± 0.089
High Myopia (*n* = 37)	0.708 ± 0.183[b]	0.531 ± 0.124[b]	0.364 ± 0.190
p value	0.000*	0.000*	0.161
Emmetropes (*n* = 40)	0.418 ± 0.099	0.255 ± 0.061	0.221±0.116

RMS, root mean square; CHOA, corneal higher-order aberrations; SA, spherical aberration; [a] and [b], the same letters indicate a not-significant difference between groups based on Scheffe multiple comparison test; *p* value* < 0.05.

Previous studies have reported the importance of SA related to deteriorating the quality of vision after refractive surgery [10, 11]. The increase of SA also causes an increase of total HOAs in both ocular and corneal aberrations. The quality of retinal image, corresponding to the corneal HOA map by Landolt's Ring simulation in the normal cornea and conventional LASIK-treated cornea, is shown in Fig. 3. It shows the difference in visual quality according to corneal HOAs in the normal cornea and LASIK-treated cornea.

The findings showed that corneal total HOAs for a 6-mm pupil were greater in the myopic refractive-surgery group than in the emmetropia group, and the higher the myopic correction achieved, the higher the induction of corneal total HOAs and SA. Thus, the results of this study are similar to those reported in previous studies with conventional myopic ablation [12-14].

Figure 4, meanwhile, demonstrates simulated wave-front maps for ocular total HOA for the eye with refractive error and myopia corrected by glasses or contact lenses, compared to the wave-front map for emmetropia. LASIK or LASEK is deemed to be the most effective method of correcting refractive errors, despite that it can be seen that HOAs of corneas corrected by LASIK or LASEK were increased, compared to corneas corrected using optical instruments such as glasses or contact lenses. This can be explained by the following: There is no change in shape of the cornea corrected by an optical instrument such as a contact lens or glasses, and it has been feasible to reduce the amount of SA with lens surface of aspheric design for each lens power [15-17].

This study finds that corneal HOAs for a 6-mm pupil were higher than for a 4-mm pupil, in both the emmetropia and myopic refractive-surgery groups. The finding agrees

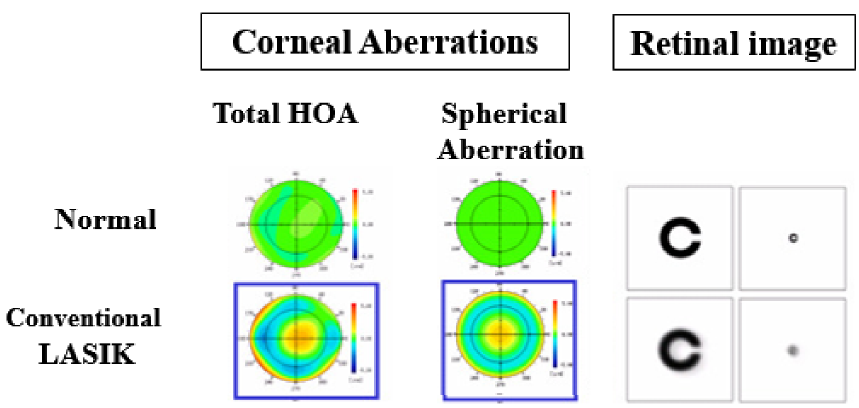


FIG. 3. Eye examples of simulated retinal image, to compare the results corresponding to the corneal total higher-order aberration and spherical aberration, in the normal and myopic refractive-surgery groups, by KR-1W.

with previous studies that the effect of ocular and corneal aberrations on the quality of vision relies on pupil size [8, 18], on which the amount of SA also depends.

The relationship between spherical equivalent (SE) of the achieved correction and ablation depth for the myopic refractive-surgery group is shown in Fig. 5. The higher the amount of myopic correction achieved, the greater the ablation depth. There was high correlation between SE of the achieved correction and ablation ($r = -0.918$, $p < 0.0001$).

The correlations between the amount of induced corneal SA with SE of the achieved myopic correction and corneal asphericity, for a 6-mm pupil in the myopic refractive-surgery group, are shown in Fig. 6. The higher the myopic correction achieved, the higher the induction of positive corneal SA ($r = -0.385$, $p < 0.0001$). The corneal asphericity Q value describes the rate of variation in the curvature of the cornea from its center to the periphery [19, 20]. Corneal asphericity after refractive surgery shifts toward oblateness. In this study, the greater the increase in Q value representing corneal asphericity, the greater the magnitude of the induced corneal SA ($r = 0.573$, $p < 0.0001$).

In the present study, the amounts of induced SA and corneal asphericity after refractive surgery were significantly correlated with the increase of the positive Q value, as ablation depth increased. These results indicate that the positive Q value is related to the amount of corneal ablation depth for refractive-error correction, according to the degree of preoperative refractive error. This study agrees with the findings of Yamane *et al.* [21], who reported that

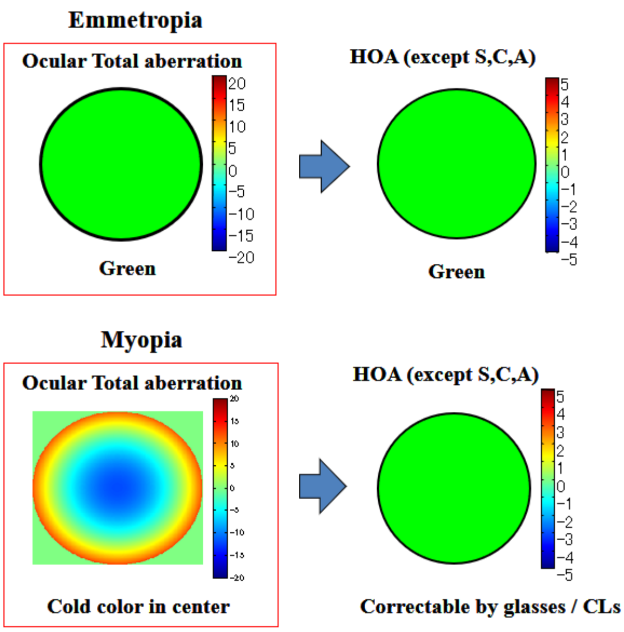


FIG. 4. Wave-front maps simulated by KR-1W for ocular total aberration, for emmetropia, myopia, and myopia corrected by glasses or contact lenses.

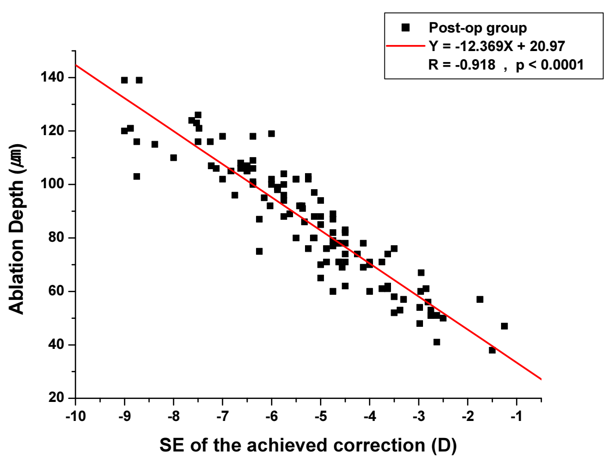
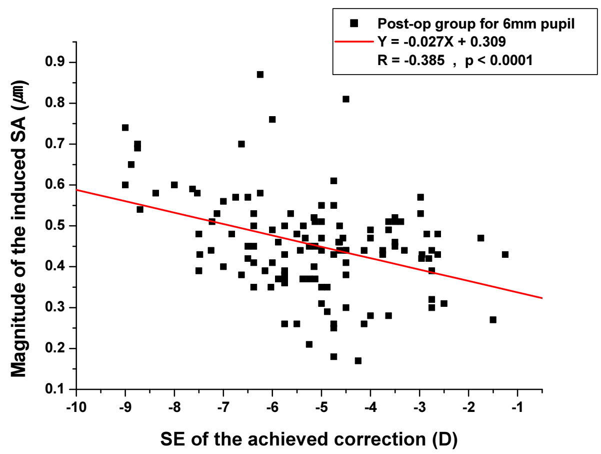
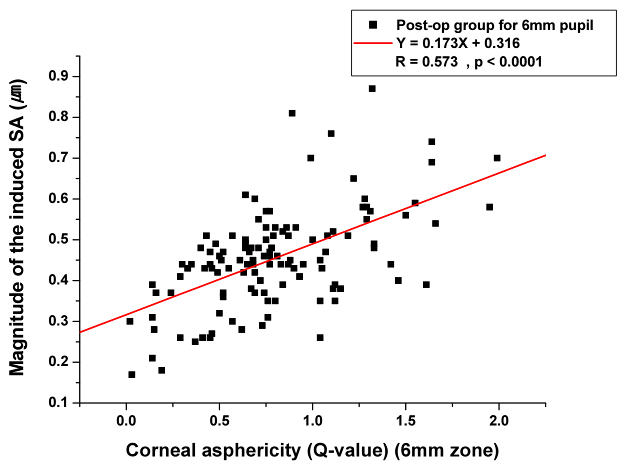


FIG. 5. Scatter plots showing the correlation between spherical equivalent (SE) of the achieved myopic correction and ablation depth, in the myopic refractive-surgery group.



(a)



(b)

FIG. 6. Scatter plots showing the correlations between (a) spherical equivalent (SE) of the achieved myopic correction and (b) corneal asphericity with the induced corneal spherical aberration (SA), for a 6-mm pupil of the myopic refractive-surgery group.

the degree of corneal ablation was related to the increase in optical aberrations. Furthermore, Bottos and Holladay *et al.* [22, 23] reported that the correlation between Q value and SA was very high, and that the amount of SA increases as the positive Q value increases. In case of myopic refractive surgery, the greater the increase in the amount of myopic correction achieved, the greater the increase in the induced corneal SA, which may affect visual quality.

IV. CONCLUSION

The central corneal curvature in myopic refractive surgery changes to an oblate corneal shape, where the radius of curvature in the mid-periphery of the cornea is smaller than the radius of curvature of the central cornea. This change in corneal shape would act as an optical factor to deteriorate the quality of the retinal image, and seems to be one of the important factors related to visual quality. Therefore, providing information about the optical response of the cornea according to the degree of corneal ablation associated with the amount of achieved correction would be helpful, for prognosis of the optimal quality of vision in prospective myopic refractive-surgery patients.

REFERENCES

1. D. Smadja, G. R. Mello, M. R. Santhiago, and R. R. Krueger, “Wavefront ablation profiles in refractive surgery: description, results, and limitations,” J. Refract. Surg. **28**, 224-232 (2012).
2. J. Porter, A. Guirao, I. G. Cox, and D. R. Williams, “Monochromatic aberrations of the human eye in a large population,” J. Opt. Soc. Am. A **18**, 1793-1803 (2001).
3. J. F. Castejón-Mochón, N. López-Gil, A. Benito, and P. Artal, “Ocular wave-front aberration statistics in a normal young population,” Vision Res. **42**, 1611-1617 (2002).
4. J. S. McLellan, S. Marcos, and S. A. Burns, “Age-related changes in monochromatic wave aberrations of the human eye,” Invest. Ophthalmol. Vis. Sci. **42**, 1390-1395 (2001).
5. J. Liang and D. R. Williams, “Aberrations and retinal image quality of the normal human eye,” J. Opt. Soc. Am. A **14**, 2873-2883 (1997).
6. E. Moreno-Barriuso, J. M. Lloves, S. Marcos, R. Navarro, L. Llorente, and S. Barvero, “Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing,” Invest. Ophthalmol. Vis. Sci. **42**, 1396-1403 (2001).
7. T. Kohnen and J. Buhren, “Corneal first-surface aberration analysis of the biomechanical effects of astigmatic keratotomy and a microkeratome cut after penetrating keratoplasty,” J. Cataract Refract. Surg. **31**, 185-189 (2005).
8. W. N. Charman and N. Chateau, “The prospects for super-acuity: limits to visual performance after correction of monochromatic ocular aberration,” Ophthalmic Physiol. Opt. **23**, 479-493 (2003).
9. K. M. A. Tuan and D. Chernyak, “Corneal asphericity and visual function after wavefront-guided LASIK,” Optom. Vis. Sci. **83**, 605-610 (2006).
10. M. Sharma, B. S. Wachler, and C. C. Chan, “Higher-order aberrations and relative risk of symptoms after LASIK,” J. Refract. Surg. **23**, 252-256 (2007).
11. M. R. Chalita, S. Chavala, M. Xu, and R. R. Krueger, “Wavefront analysis in post-LASIK eyes and its correlation with visual symptoms, refraction, and topography,” Ophthalmology **111**, 447-453 (2004).
12. D. Smadja, M. R. Santhiago, G. R. Mello, D. Touboul, M. Mrochen, and R. R. Krueger, “Corneal higher order aberrations after myopic wavefront-optimized ablation,” J. Refract. Surg. **29**, 42-48 (2013).
13. T. Oshika, K. Miyata, T. Tokunaga, T. Samejima, S. Amano, S. Tanaka, and T. Fujikado, “Higher order wavefront aberrations of cornea and magnitude of refractive correction in laser in situ keratomileusis,” Ophthalmology **109**, 1154-1158 (2002).
14. D. Gatinel, P. A. Adam, S. Chaabouni, J. Munck, M. Thevenot, T. Hoang-Xuan, and H. S. Bains, “Comparison of corneal and total ocular aberrations before and after myopic LASIK,” J. Refract. Surg. **26**, 333-340 (2010).
15. T. C. Vaz and R. E. Gundel, “High-and low-contrast visual acuity measurements in spherical and aspheric soft contact lens wearers,” Cont. Lens Ant Eye **26**, 147-151 (2003).
16. S. Efron, N. Efron, and P. B. Morgan, “Optical and visual performance of aspheric soft contact lenses,” Optom. Vis. Sci. **85**, 201-210 (2008).
17. J. M. Kim and K. J. Lee, “Comparison higher-order aberration and visual quality in eyes wearing aspheric and spherical silicone hydrogel contact lenses,” Korean J. Vis. Sci. **17**, 343-354 (2015).
18. J. L. Nguyen-Khoa, J. J. Gicquel, D. A. Lebuisson, P. Digiero, and M. Maille, “Monochromatic ocular aberrations distribution in professional pilots,” Invest. Ophthalmol. Visual Sci. **46**, E-Abstract 1998 (2005).
19. J. H. Yoon, K. Avudainayagam, C. Avudainayagam, and H. A. Swarbrick, “Validating a new approach to quantify Posperior corneal curvature in vivo,” J. Korean Ophthalmic Opt. Soc. **17**, 223-232 (2012).
20. J. M. Gonzalez-Meijome, C. Villa-Collar, R. Montes-Mico, and A. Gomes, “Asphericity of the anterior human cornea with different corneal diameters,” J. Cataract Refract. Surg. **33**, 465-473 (2007).
21. N. Yamane, K. Miyata, T. Samejima, T. Hiraoka, T. Kiuchi, F. Okamoto, and T. Oshika, “Ocular higher-order aberrations and contrast sensitivity after conventional laser in situ keratomileusis,” Invest. Ophthalmol. Visual Sci. **45**, 3986-3990 (2004).
22. K. M. Bottos, J. B. Ko, M. A. Isidro, N. Wongpitoompyia, N. H. O. Camara, M. T. Leite, T. Purcell, D. J. Schanzlin, “Corneal asphericity and spherical aberration after refractive surgery,” J. Cataract Refract. Surg. **37**, 1109-1115 (2011).
23. J. T. Holladay and J. A. Janes, “Topographic changes in corneal asphericity and effective optical zone after laser in situ keratomileusis,” J. Cataract Refract. Surg. **28**, 942-947 (2002).