Comparison of Higher-order Aberrations between Eyes with Natural Supervision and Highly Myopic Eyes in Koreans

Min Kim, MD,1 Young Gi Lee, MD,2 Kyung Ryul Seo, MD,1 Eung Kweon Kim, MD,1 Hyung Keun Lee, MD,1

Department of Ophthalmology, Yonsei University College of Medicine1, Seoul, Korea
Seran Eye Center2, Seoul, Korea

Purpose: To describe the characteristics and investigate the differences of higher-order aberrations (HOAs) between the eyes with a natural, uncorrected visual acuity (UCVA) of 20/12 and eyes with highly myopic eyes in Korean adults.

Methods: Thirty-one eyes of 20 subjects with UCVA of 20/12 (Group 1) and 54 eyes of 36 myopic patients with greater than -6 diopters (Group 2) were analyzed for type and magnitude of HOAs across a 6.0 mm pupil. HOAs were measured by Wavescan (VISX, Santa Clara, CA, USA) in natural scotopic conditions and were presented as root-mean-square (RMS:μm) in Belle aberration maps.

Results: The mean spherical equivalent (SE) of manifest refraction was -0.15±0.25 D (range: +0.37 to -0.50 D) in Group 1 and -7.25±0.78 D (range: -6.00 to -9.25 D) in Group 2. The total root-mean-square (RMS) values of HOAs for Group 1 and Group 2 were 0.28±0.09 μm and 0.27±0.087 μm, respectively (P>0.05). The mean values of coma, trefoil, and spherical aberration were 0.14±0.091 μm, 0.14±0.089 μm, 0.091±0.059 μm in Group 1 and 0.16±0.077 μm, 0.14±0.073 μm, 0.082±0.059 μm in Group 2, respectively.

Conclusions: This study helped establish ocular aberration standards for those with natural supervision and those with highly myopic eyes among Koreans. Individuals with natural supervision had significant amounts of HOAs, and there was no significant difference in the amount of HOAs between the two groups. The index of higher-order aberrations may not be a perfect predictor of the amount of refractive error.

Korean Journal of Ophthalmology 21(2):79-84, 2007

Key Words: Higher-order aberrations, Supervision, High myopia

New optical technology using wavefront sensing has made it possible to measure and assess the optical properties of the eye beyond the sphere and cylinder shapes and to measure irregular astigmatism as a higher-order wavefront aberration.1-4 Correction of irregular astigmatism and higher-order aberrations by wavefront-guided refractive surgery would theoretically enable us to obtain supernormal vision, which is defined as a natural, uncorrected visual acuity (UCVA) of 20/15 or better.1-4 Since the advent of wavefront technology, the relation of wavefront analysis to an excimer laser system for customized corneal ablation has supported human efforts to optimize human visual performance and to achieve the dream of acquiring supervision. In fact, wavefront-guided refractive surgery has improved postoperative visual quality and patient's satisfaction levels, particularly in low and middle-ranged myopia, compared to traditional LASIK surgery.5,6 Many studies have suggested that reduced higher-order aberrations could improve visual acuity as well as visual quality.7

Despite the development of wavefront technology and the advancements in refractive surgery in recent years, the clinical significance of HOAs and their role in refractive surgery have not been fully explained.8 Cheng et al. found that there was no correlation between wavefront aberrations and the refractive error of normal eyes,9 but no studies comparing the HOAs between supernormal vision and high myopia have been performed to date. Previous studies on the ocular HOAs have mainly involved Western adult populations, and to date, there have been no published studies describing the characteristics of ocular higher-order aberrations in Korean adults with supervision and high myopia. Data regarding the characteristics of ocular aberrations in the natural supervision as well as the high myopia group would be valuable for both diagnostic and clinical treatment purposes.
The present study was designed to describe the distribution of wavefront aberrations and to reveal whether a difference of higher-order aberrations (HOAs) exists between the eyes with natural uncorrected visual acuity (UCVA) of 20/12 and highly myopic eyes.

**Materials and Methods**

**Instrument and Measurements**

Higher-order aberrations were measured by Wavescan (VISX, Santa Clara, CA, USA) in natural scotopic conditions across a 6.0 mm pupil. The Wavescan is a diagnostic instrument designed to measure and display wavefront aberrations using a Hartmann-Shack wavefront sensor. It shines a dim laser beam, approximately 1 mm in diameter onto the retina, close to the fovea, and analyzes the reflected light via an array of microlenses, a charge-coupled device (CCD) array, and a software algorithm. The location of each spot gathered from the video sensor is then compared to the theoretical ideal locations, and the software computes the wavefront map of the aberrations. The wavefront measurements were performed in accordance with the manufacturer's guidelines. Two different acuity maps were used to acquire data: a point spread function graphic, and the individual description of each aberration, which included total aberrations (root-mean-square (RMS) error from the acuity map), higher-order aberrations (RMS error from the wavefront higher-order aberrations map), effective blur, and the level of each individual aberration from the normalized polar Zernike coefficient table. Higher-order aberrations were measured out to the 6th Zernike order.

**Subjects**

Thirty-one eyes of 20 subjects with UCVA of 20/12 (Group 1) and 54 eyes of 36 myopic patients with more than -6.00 diopters (Group 2) were analyzed for type and magnitude of HOAs across a 6.0 mm pupil. The study was conducted in adherence to the tenets of the Declaration of Helsinki. Subjects were excluded if they met any one of the following criteria: connective tissue disease, diabetes mellitus, amblyopia, corneal disease, cataracts, glaucoma, previous ocular trauma, retinal disease or discontinued lens wear less than eight weeks before the Wavescan measurement for rigid gas-permeable lenses, four weeks for toric soft lenses, and two weeks for soft lenses that could alter the wavefront measurement. In addition, those who were taking medications that could affect accommodation were excluded. Data from eyes whose wavefront analysis was found to be unreliable were also not included, as indicated by two or more red lights at the review screen. All subjects had manifest refraction, intraocular pressure measurements, and corneal topography taken. Higher-order aberrations were measured by Wavescan (VISX) in natural scotopic conditions; only wavefront data across pupils with a diameter of 6.0 mm were included.

**Analysis of Wavefront Aberrations**

Zernike polynomials were used to decompose the measured wavefront into its corresponding aberration components. The higher-order aberrations were presented as root-mean-square (RMS; µm) in Belle aberration maps, which displayed higher-order aberrations from the 6.0 mm pupil measurement condition. Parameters to be analyzed were (1) Zernike coefficients from the 3rd to the 6th orders; (2) root mean square (RMS) of HOAs from the 3rd to the 6th orders; (3) RMS of the total coma (square root of the sum of the squared coefficients of Z31 and Z51); (4) RMS of the total trefoil (square root of the sum of the squared coefficients of Z33 and Z53); and (5) RMS of the total spherical aberration (SA) (square root of the sum of the squared coefficients of Z40 and Z60).

Data were analyzed using the Statistical Program for Social Sciences (SPSS) version 12.0. The distribution of HOAs from the 3rd to the 6th orders in both groups was investigated, and the differences in the mean values of HOAs, total coma, total trefoil, and total SA were compared and analyzed using unpaired t-tests. A probability of less than 5% (P<0.05) was considered statistically significant.

**Results**

The demographic and refractive summaries of the subjects in each group are shown in Table 1.

**Distribution of Corneal Wavefront Aberrations**

**Zernike Coefficients**

The absolute values, standard deviations, and ranges were highest for the 3rd order terms and tended to decrease gradually up to the 6th order. Each factor of HOAs showed no significant difference between the two groups (Table 2). For low-order aberrations, there was a statistically significant
differences between the two groups; the mean values detected for defocus and astigmatism were 1.25 (range: -0.7 to 4.75 µm) and 0.416 (range: 0.02 to 2.00 µm) in Group 1 and 4.531 (range: 2.23 to 7.07 µm) and 0.722 (range: 0.05 to 2.21 µm) in Group 2, respectively.

**Total HOAs**

The mean root-mean-square (RMS) values of Group 1 and Group 2 for total HOAs were 0.28±0.09 µm and 0.275±0.087 µm, respectively (p<0.05) (Table 2). The mean RMS values for each order decreased progressively from the 3rd order to the 6th order. Fig. 1 represents the comparison of total HOAs as well as other higher-order individual aberrations, and no statistically significant difference was observed between the two groups (p>0.05).

**Spherical Aberration (Z40), Coma (Z31) and Trefoil (Z33)**

The mean values of coma, trefoil, and spherical aberrations in Group 1 were 0.137±0.091 µm, 0.136±0.089 µm, and 0.091±0.059 µm, respectively. In Group 2, the mean values of coma, trefoil, and spherical aberration were 0.156±0.077, 0.139±0.073, and 0.082±0.059 (Table 2).

**RMS of total SA, Coma, and Trefoil**

The mean RMS values of total coma, trefoil, and spherical aberration (SA) were 0.146±0.0845 µm, 0.147±0.0835 µm, and 0.096±0.057 µm in Group 1 and 0.162±0.075 µm, 0.146±0.069 µm and 0.088±0.057 µm in Group 2.

**Discussion**

A fundamental understanding regarding the distribution of higher-order aberrations (HOAs) of the human eyes with supernormal vision and high myopia is essential from a clinical point of view, since wavefront-guided refractive surgery has recently become a very popular method. This encouraged us to evaluate the clinical significance of HOAs in relation to visual acuity and to describe the characteristics of total HOAs and the RMS of total HOAs in each group. There was no statistically significant difference between the two groups (Table 3).

Fig. 1. Comparison of total HOAs and individual higher-order aberrations of each group. HOAs=higher-order aberrations, SA=spherical aberration.

**Table 2.** Mean coefficients (µm) for each Zernike term from the 3rd to the 6th order in the supernormal vision and the high myopia groups.

| Zernike Coefficient | Supernormal Vision (Group 1) Mean±SD* (µm) | High Myopia (Group 2) Mean±SD* (µm) | P value |
|---------------------|------------------------------------------|-------------------------------------|---------|
| Z20                 | 1.25±1.24                                | 4.531±1.197                         | 0       |
| Z22                 | 0.416±0.42                               | 0.722±0.534                         | 0.005   |
| Z31                 | 0.137±0.091                              | 0.156±0.077                         | 0.337   |
| Z33                 | 0.136±0.089                              | 0.139±0.073                         | 0.858   |
| Z40                 | 0.091±0.059                              | 0.082±0.059                         | 0.516   |
| Z42                 | 0.065±0.057                              | 0.051±0.033                         | 0.28    |
| Z44                 | 0.065±0.033                              | 0.068±0.035                         | 0.733   |
| Z51                 | 0.034±0.019                              | 0.036±0.022                         | 0.681   |
| Z53                 | 0.035±0.027                              | 0.029±0.021                         | 0.372   |
| Z55                 | 0.039±0.027                              | 0.028±0.018                         | 0.054   |
| Z60                 | -0.007±0.027                             | -0.005±0.025                        | 0.811   |
| Z62                 | 0.026±0.018                              | 0.021±0.011                         | 0.218   |
| Z64                 | 0.024±0.016                              | 0.025±0.015                         | 0.711   |
| Z66                 | 0.032±0.025                              | 0.029±0.017                         | 0.566   |
| RMS of total HOA‡   | 0.28±0.09                               | 0.275±0.087                         | 0.808   |

*SD=standard deviation, †RMS=root mean square, ‡HOA=higher-order aberration.
of HOAs in adult Korean eyes with supernormal vision and high myopia by investigating the difference of HOAs between the eyes with natural, uncorrected visual acuities (UCVA) of 20/12 and highly myopic eyes. In agreement with previous reports, the average RMS of HOAs decreased with increasing order, and the 3rd order predominated. Past studies have indicated that there is a low correlation between ocular wavefront aberrations and visual performance in the low ocular aberration range. The results of this study correspond with the findings of earlier studies which have reported that HOAs in eyes with natural, supernormal vision are not negligible or comparable to HOAs in myopic eyes. Netto et al. analyzed 418 eyes of 226 refractive surgery candidates and showed that there was no statistically significant difference in wavefront measurements between different groups of patients separated according to the spherical equivalent of refraction. In accordance with these earlier findings from studies involving Western populations, the results of this study clearly showed that Korean individuals with natural, supernormal vision have a significant amount of HOAs and also demonstrated that there was no significant difference in the amount of HOAs between the supernormal vision and the high myopia groups, implying that the amount of refractive error may not be a predictive factor for HOAs.

If there were indeed no correlations between HOAs and refractive status, what would be the potential effectiveness of correcting HOAs in refractive surgery? In a quest for achieving an aberration-free optical system, wavefront-guided refractive surgery has improved postoperative visual quality and patient's satisfaction levels compared to traditional LASIK surgery. However, in one study, wavefront-guided LASIK using Zyoptix 3.1 was performed for the treatment of myopia and myopic astigmatism, and although in close to half of the eyes HOAs could be reduced, there was still undercorrection and induction of HOAs with the algorithm employed. In their study, Levy et al. pointed out that the RMS wavefront error of normal eyes has a low correlation with visual performance and that the elimination of HOAs during laser refractive surgery might not be necessarily beneficial after all. Theoretically, a small RMS value should result in good optical quality, and a larger RMS value should result in poorer optical quality, but the opposite is not always true as was shown in this study. This suggests that the higher-order RMS could be loosely associated with the best-corrected visual acuity. It is possible that the main clinical significance of wavefront technology in refractive surgery today is not to reduce physiological HOAs to achieve supervision, but rather to avoid new high-order aberrations which could be induced by the surgical correction of low-order aberrations (defocus, astigmatism).

Although we cannot explain the clinical significance of physiological HOAs and account for the lack of difference between the two groups, there are some hypotheses to explain the difference. First of all, because of the limitations inherent in the wavefront technology, it might not have detected possible subtle differences between the two groups. The Hartmann-Shack system utilizes an array of 13×19 microlenses with apertures of 0.5 mm, so the wavefront aberrations smaller than the sizes of these microlenses cannot be recognized simply as a single wavefront and could not be detected despite the possibility that it might bear clinical significance. The reflected wavefront of light smaller than the microlenslet array would be recognized as a single wavefront and could not be detected.

### Table 3. Mean RMS values (µm) in the supernormal vision group and the high myopia group.

|                      | Supernormal vision | High myopia | P value |
|----------------------|--------------------|-------------|---------|
| Total RMS of HOAs‡   | 0.28±0.09          | 0.275±0.087 | 0.808   |
| Coma‡                | 0.137±0.091        | 0.156±0.077 | 0.337   |
| Trefoil§             | 0.136±0.089        | 0.139±0.073 | 0.858   |
| Spherical aberration† | 0.091±0.059        | 0.082±0.059 | 0.516   |
| Total coma§          | 0.146±0.0845       | 0.162±0.075 | 0.118   |
| Total trefoil**      | 0.147±0.0835       | 0.146±0.069 | 0.784   |
| Total SA††           | 0.096±0.057        | 0.088±0.057 | 0.175   |

* RMS=root mean square, †HOAs=higher-order aberrations, 3rd order to 6th order; ‡Coma=Z31, § Trefoil=Z33, ††Spherical aberration=Z40, †Total Coma=square root of the sum of the squared coefficients of Z31 and Z51, †Total Trefoil=square root of the sum of the squared coefficients of Z33 and Z53, †Total SA=square root of the sum of the squared coefficients of Z40 and Z60.
imperfections in this instrumentation, errors in registration, poor pupil centration, measurement noise, and other technical factors that could contribute to the inaccurate measurement of wavefront aberrations in the eye could possibly blind us from any subtle differences of HOAs between the two groups. A limitation to this device has already been discussed by Wang et al. in their study which showed that larger HOAs causes crossover effects hindering accurate measurement of wavefront analysis. 

In this present study, defocus and astigmatism were found to be the most significantly different aberrations between the high myopia group and the supernormal vision group. Previous studies have demonstrated that defocus and astigmatism are the most significant aberrations of all the ocular aberrations in both patients being evaluated for refractive surgery and the general population and this study corroborated this finding. The findings in this study are consistent with the previous report that the correction of lower-order aberrations is an important determinant of visual quality, but this study showed that the amount of refractive error may not be a predictive factor for HOAs. This raises issues about which measurement parameters should be used in wavefront-guided refractive surgery and also brings up questions as to whether the elimination of HOAs should be a prerequisite in refractive surgery.

There are a few limitations to this study. First of all, the correlation between ocular HOAs and age was not analyzed due to a relatively narrow age range. The age distribution in this study included mostly patients in their 20s and 30s, and previous studies have already demonstrated that higher-order aberrations increased slightly with increasing age. Secondly, devices used in this study and in other studies are not identical, and ocular aberrations are measured up to the 6th order in this study, whereas in other studies they were measured up to the 8th orders. Previous studies have shown that the mean RMS values for each order decrease progressively from the 3rd order and higher, so it is probable that the contribution of the 7th and 8th order to the total amount of ocular aberrations is not significant, and therefore could be ignored in this study. Thirdly, only visual acuity was discussed as an index of quality of vision. However, contrast sensitivity, low-contrast visual acuity, visual acuities measured at different levels of luminance, and glare should all be considered for better evaluation of visual quality. In addition, there are some limitations in the metrics used in the present study: Marsack, Thibos, and Applegate demonstrated the need for different metrics other than RMS wavefront error to quantify the effects of low levels of aberration on visual acuity.

In summary, this study evaluated HOAs of Korean individuals with natural supervision and high myopia for the first time and found that individuals with natural supervision have a significant amount of HOAs and that there was no significant difference in the amount of HOAs between the two groups. These results imply that the index of higher-order RMS is not a perfect predictor of the quality of vision and provides additional evidence for the lack of correlation between the amount of refractive error and HOAs. This study helps establish ocular aberration standards for the natural supervision group and high myopia in Koreans, particularly among refractive surgery candidates.

References

1. Maeda N. Wavefront technology in ophthalmology. Curr Opin Ophthalmol 2001;12:294-9.
2. We RH, Penney CM, Thompson KP. Measurement of ocular wavefront distortion with a spatially resolved refractometer. Appl Optics 1992;31:3678-86.
3. Liang J, Grimm B, Goezl S, Bille JF. Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. J Opt Soc Am A Opt Image Sci Vis 1994;11:1949-57.
4. Liang J, Williams DR, Miller DT. Supernormal vision and high-resolution retinal imaging through adaptive optics. J Opt Soc Am A Opt Image Sci Vis 1997;14:2884-92.
5. Kohen T, Buhren J, Kuhne C, Mirshahi A. Wavefront-guided LASIK with the Zyoptix 3.1 system for the correction of myopia and compound myopic astigmatism with 1-year follow-up: clinical outcome and change in higher order aberrations. Ophthalmology 2004;111:2175-85.
6. Hammer T, Duncker GI, Giessler S. Results of wavefront-guided LASIK. Ophthalmologe 2004;101:824-9.
7. Seiler T, Dastjerdi MH. Customized cornel ablation. Curr Opin Ophthalmol 2002;13:256-60.
8. Applegate RA, Marsack JD, Ramos R, Sarver EJ. Interaction between aberrations to improve or reduce visual performance. J Cataract Refract Surg 2003;29:1487-95.
9. Cheng X, Bradley A, Hong X, Thibos LN. Relationship between refractive error and monochromatic aberrations of the eye. Optom Vis Sci 2003;80:43-9.
10. Thibos LN, Hong X. Clinical applications of the Shack-Hartmann aberrometer. Optom Vis Sci 1999;76:817-25.
11. Molebny VV, Panagopoulos SI, Molebny SV. Principles of ray tracing aberrometry. J Refract Surg 2000;16:S572-5.
12. Howland HC. The history and methods of ophthalmic wavefront sensing. J Refract Surg 2000;16:S552-3.
13. Thibos LN. Principles of Hartmann-Shack aberrometry. J Refract Surg 2000;16:S553-5.
14. Applegate RA, Hilimantel G, Howland HC. Corneal first surface optical aberrations and visual performance. J Refract Surg 2001;16:507-14.
15. Levy Y, Segal O, Avni I, Zadok D. Ocular Higher-order Aberrations in Eyes With Supernormal Vision. Am J Ophthalmol 2005;139:225-8.
16. Netto MV, Ambrosio R Jr, Shen TT, Wilson SE. Wavefront analysis in normal refractive surgery candidates. J Refract Surg 2005;21:332-8.
17. Mintsioulis G, Munger R, Al-Muammar A. Wavefront Technology. In : Krachmer JH, Mannis MJ, Holland EJ. eds. Cornea, 2nd ed. Philadelphia : Mosby Inc, 2004; v. 2. chap. 168
18. Wilson SE. Wavefront analysis: are we missing something? Am J Ophthalmol 2003;136:340-2.
19. Wang Y, Zhao K, Jin Y et al. Changes of higher order aberration with various pupil sizes in the myopic eye. J Refract Surg 2003;19:8270-4.
20. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. J Opt Soc Am A Opt Image Sci Vis 2001;18:1793-803.
21. Wang L. Koch DD. Ocular higher-order aberrations in
individuals screened for refractive surgery. J Cataract Refract Surg 2003;29:1896-903.

22. Oshika T, Klyce SD, Applegate RA, Howland HC. Changes in corneal wavefront aberrations with aging. Invest Ophthalmol Vis Sci 1999;40:1351-5.

23. Marsack JD, Thibos LN, Applegate RA. Metrics of optical quality derived from wave aberrations predict visual performance. J Vis 2004;4:322-8.