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

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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.

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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.

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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.[10-13] 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

Table 1. Demographic and refractive characteristics of the supernormal vision group and the high myopia group.

	Supernormal vision (Group 1)	High myopia (Group 2)
Number of eyes	31 eyes (R‡:14, L§:17)	55 eyes (R‡:27, L§:28)
Sex ratio (M:F)	9:22	9:46
Mean age (years)	27.9±4.7	29.2±6.6
UCVA*	20/12	<20/200
BCVA	-	20/15
Mean SE† (diopters)	-0.15±0.25	-7.25±0.78

* UCVA=uncorrected visual acuity, † SE=spherical equivalents, ‡: R=Right eye, § L=Left eye.

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, respectively. There was no statistically significant difference between the two groups (Table 3).

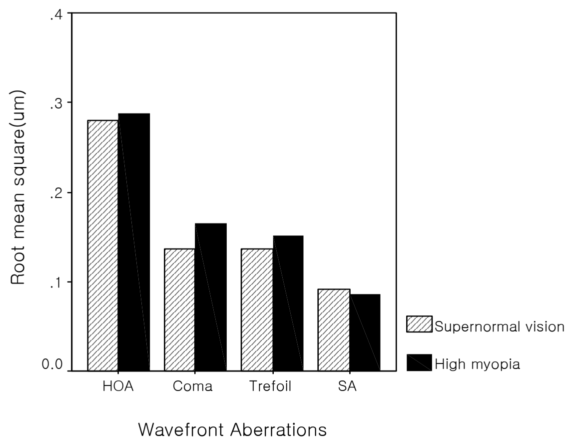

Fig. 1. Comparison of total HOAs* and individual higher-order aberrations of each group.
*HOAs=higher-order aberrations, SA=spherical aberration.

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

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	0.063±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.

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.

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.[14] 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.[15] 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.[16] 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.[5] 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.[15] Theoretically, a small RMS value should result in good optical quality, and a larger RMS value should result in poorer optical quality,[17] 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,[13] so the wavefront aberrations smaller than the sizes of these microlenses cannot theoretically be detected by the Hartmann-Shack microsensor, but they could still bear clinical significance. The reflected wavefront of light smaller than the microlenslet array would be recognized simply as a single wavefront and could not be detected despite the possibility that it might bear clinical significance. Another possible explanation is the role of the central nervous system on the perception of our vision. The effects of central processing of visual information in the brain not accounted for by the wavefront technology might be greater than we have expected. The complex and subtle interrelationships between the wavefront aberrations and the interacting central nervous system could affect astigmatism, coma, trefoil, and other HOAs.[18] Currently, there are no aberrometers that could provide any information about the processing of visual input by the central nervous system. In addition, there are limitations to the devices used in this study. Wavefront technology is still in its infancy;

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.[19]

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[17,20] 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 3error 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.[14,21,22] 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,[21,22] 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.[23]

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.

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