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Peripheral Aberrations and Image Quality for Contact Lens Correction

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Abstract

Purpose—Contact lenses reduced the degree of hyperopic field curvature present in myopic eyes and rigid contact lenses reduced sphero-cylindrical image blur on the peripheral retina, but their effect on higher order aberrations and overall optical quality of the eye in the peripheral visual field is still unknown. The purpose of our study was to evaluate peripheral wavefront aberrations and image quality across the visual field before and after contact lens correction.

Methods—A commercial Hartmann-Shack aberrometer was used to measure ocular wavefront errors in 5° steps out to 30° of eccentricity along the horizontal meridian in uncorrected eyes and when the same eyes are corrected with soft or rigid contact lenses. Wavefront aberrations and image quality were determined for the full elliptical pupil encountered in off-axis measurements.

Results—Ocular higher-order aberrations increase away from fovea in the uncorrected eye. Third-order aberrations are larger and increase faster with eccentricity compared to the other higher-order aberrations. Contact lenses increase all higher-order aberrations except 3rd-order Zernike terms. Nevertheless, a net increase in image quality across the horizontal visual field for objects located at the foveal far point is achieved with rigid lenses, whereas soft contact lenses reduce image quality.

Conclusions—Second order aberrations limit image quality more than higher-order aberrations in the periphery. Although second-order aberrations are reduced by contact lenses, the resulting gain in image quality is partially offset by increased amounts of higher-order aberrations. To fully realize the benefits of correcting higher-order aberrations in the peripheral field requires improved correction of second-order aberrations as well.

Keywords

myopia; peripheral aberration; image quality; contact lenses; wavefront aberrometry

It is well known that the human eye does not produce perfectly focused images on the retina. The image formed on the retina is degraded by optical aberrations caused by imperfections of ocular refractive components. Refractive errors, also called lower-order aberrations (LOA), are the most common ocular aberrations and they have been studied for many years. However, human eyes also have higher-order aberrations (HOA). Vertical coma (Z_3^{-1}), horizontal coma (Z_3^1) and spherical aberration (Z_4^0) are the most important higher-order

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aberrations since they present in higher amounts than the other higher-order aberrations in the population.^{1, 2}

While previous studies paid more attention to measuring and understanding foveal aberrations, interest in aberrations associated with peripheral vision has increased dramatically in recent years because the quality of off-axis optics is important for fundus imaging, motion and orientation detection, and may be important for the development of refractive error.^{3–10} Researchers hypothesized that high levels of aberrations will influence ocular elongation caused by degraded retinal images^{11–15} thus modulating growth of the eye intended to minimize retinal image blur over a wide field of view (the “grow to clarity” model).¹⁶ Thus peripheral aberrations and image quality might be critical factors for the development of central refractive error.

Contact lenses (CLs) are widely used treatments for refractive errors. They aim to optimize foveal vision by correcting refractive errors (defocus and astigmatism). The on-axis optical quality after wearing contact lenses has been well studied both by theoretical calculation and experimental measurements.^{17–19} Hong et al.¹⁸ and Dorronsoro et al.²⁰ have measured on-axis aberrations in subjects wearing RGP (Rigid-Gas-Permeable) lenses, finding that RGP lenses provided lower level of aberrations than SCLs (Soft Contact Lenses) and spectacle lenses. They concluded that wearing RGP lenses can significantly reduce not only defocus and astigmatism, but also higher-order aberrations in central vision. Theoretical analysis indicates that retinal image quality in peripheral vision may also benefit from improved designs of contact lenses.²¹

Compared to the understanding of on-axis aberrations with CL correction, little is known about off-axis ocular wavefront aberrations and image quality when wearing CLs. Theoretical calculations of the on-axis or off-axis aberrations of contact lenses are hampered by complex interaction between the cornea and contact lenses, and are complicated by the contribution of internal components of the eye to the total optical aberrations.^{17, 22} So a definitive account of how peripheral aberrations and image quality changes across the visual field due to contact lens correction requires an empirical, on-eye evaluation of the peripheral optical performance of the contact lenses.

Peripheral low-order aberrations have been reported in our previous paper²³ as refractive corrections in power vector notation²⁴ calculated from 2nd-order aberrations. Those results confirmed published reports^{25–28} that myopic eyes have hyperopic peripheral relative defocus (PRD, which means that spherical equivalent error in peripheral vision is positive compared to foveal vision). Furthermore, the amount of hyperopic PRD is greater in eyes with larger amounts of foveal myopic refractive error. When CLs are worn to correct central refractive errors, the amount of hyperopic PRD declines for both SCLs and RGP lenses, but it declines more for RGP lenses. In contrast, oblique astigmatism in the peripheral field increases when wearing contact lenses. This increase was greater for RGP lenses than for SCLs. The resulting increase in astigmatic blur was outweighed by the decrease in spherical blur, leaving a net improvement in retinal image quality in peripheral retina when wearing CLs. Here we expand on that previous report by describing the changes of off-axis HOA produced by CL correction of central vision. Taken together, these results provide a more complete description of how image quality changes across the visual field as a result of CL correction. Such knowledge is important for assessing the potential value of designing contact lenses that correct peripheral HOA in addition to correcting peripheral LOA. If correcting peripheral LOA fully is not possible, will image quality improve significantly by correcting peripheral HOA? The purpose of this study was to evaluate peripheral wavefront aberrations and image quality across the visual field before and after contact lens correction.

METHODS

Subjects

This study followed the tenets of the Declaration of Helsinki. Informed consent was acquired from all subjects following approval by the Indiana University institutional review board. Eleven young normal subjects (5 female and 6 males, 23 to 30 years) with myopia from -1 to -6.5 D (spherical equivalent) were included initially, but two were eliminated for reasons stated below, leaving a total of 9 subjects for whom data are presented in this report. None of the subjects had astigmatism greater than 2 D. The inclusion criteria included best corrected logMAR visual acuity of 0.00 (20/20 Snellen acuity) or better in both eyes. Clinical records were inspected to ensure all subjects had stable refractive errors over the past 12 months and were free of any ocular or systemic disease or medications. Cycloplegic drugs were not used.

Lens Design and Characteristics

We used Acuvue 2 (base curve: 8.3mm, overall diameter (OAD): 14mm) and Menicon RGP (OAD: 9.2mm, optic zone: 7.8mm, Menicon Z material with Dk (ISO) = 163) lenses. The alignment fitting strategy (fluorescein pattern shows alignment of back surface of the lens with the cornea over most of the surface)²⁹ based on individual eye's keratometry readings was used for all subjects (base curve: 7.67 ± 0.26 mm (Mean $\pm$ SD)).

Wavefront Aberration Measurement and Analysis

We used a commercial Hartmann-Shack (HS) wavefront aberrometer, COAS (Complete Ophthalmic Analysis System, AMO Wavefront Sciences, Inc., Albuquerque, New Mexico) to measure aberrations on the subject's left eye in a dark room, thereby ensuring the largest physiological pupil size. The HS aberrometer has been widely used to measure aberrations in a variety of clinical studies^{18, 30–36} due to its speed of operation and robustness to scattering of light compared to most other aberrometers.³⁷ It is a robust and reliable instrument for measuring both lower and higher order aberrations in the central visual field.^{33, 38, 39} The COAS aberrometer has been shown to be a valid instrument for measuring peripheral ocular aberrations for elliptical entrance pupils that occur in the off-axis viewing condition.⁴⁰

The COAS system is a double-pass aberrometer with a limited dynamic range set by an internal range-limiting aperture. As the measurement axis goes further into the peripheral visual field, the amount of ocular aberrations will increase on both the forward and reverse passes of light. These highly aberrated rays could be blocked by the internal aperture, which causes spots to be missing from the HS data image that in turn can lead to errors in pupillometry as well as aberrometry.

Individual differences of optical characteristics in different human eyes can therefore lead to variability in the range of eccentricities accessible for measurement. We reported previously⁴¹ that the range of eccentricities accessible in our human subjects is limited to 30° in both nasal and temporal horizontal visual field as judged by whether the illuminated lenslets in the HS wavefront sensor fill the entire entrance pupil. Since the accessible range was less than 30° for two subjects, we excluded these two subjects' data from subsequent analysis.

Since conventional Zernike analysis for reconstructing wavefront aberrations from wavefront slope data assumes the pupil is circular, to perform Zernike analysis on off-axis wavefront aberration data requires a method that is valid for elliptical entrance pupils encountered during off-axis measurements. In our previous paper,⁴⁰ we demonstrated the

validity of using commercial software CLAS-2D (Complete Light Analysis System-2D, AMO Wavefront Sciences, Inc., Albuquerque, New Mexico) to analyze off-axis data. The software allows users to draw an analysis Zernike circle that completely contains the elliptical entrance pupil. Computation of the Zernike coefficients ignores the area between the Zernike analysis circle and the elliptical entrance pupil. Having determined the Zernike coefficients, the wavefront may be reconstructed over the entire circular area used for analysis, but the region outside the elliptical pupil is an extrapolation of no interest. To display the wavefront and to compute retinal image quality, the Zernike coefficients were imported into Matlab (The Mathworks, Inc., Natick, Massachusetts) where custom software was used to reconstruct the wavefront from Zernike coefficients, apply the appropriate elliptical mask, and then compute the retinal point-spread-function (PSF) and optical transfer function (OTF) using Fourier optics.

Three measurements were taken at each visual eccentricity in 5° steps out to 30° in periphery along the horizontal meridian, with realignment of the eye to the instrument between measurements. Subjects blinked before measurements to ensure tear film integrity. Measurements were taken after the contact lens stabilized on the eye between blinks. Mean pupil diameter across all subjects was 6.89 mm and the largest pupil was 7.2 mm. We therefore used a 7.2 mm circle as a common basis for Zernike analysis of all eyes. During measurements, accommodation was controlled by providing a fixation target for subjects.

Zernike polynomials are used to describe the eye's wavefront error.⁴² Each order Zernike aberration is reported as root-mean-square (RMS) aberration value. RMS can be easily computed as the square root of the sum of the squared aberration coefficients. All results refer to 840-nm wavelength infrared laser light, which was used in COAS aberrometer. However, this method of calculating RMS becomes increasingly inaccurate when the pupil becomes more elliptical in the periphery because it tends to overestimate the true RMS over the elliptical pupil. Moreover, the true RMS is also overestimated in some subjects with smaller pupils because of extrapolation of the Zernike polynomials to the larger common analysis pupil (7.2 mm). Therefore, RMS data reported in this paper can be interpreted as an upper-bound of the actual wavefront error over the elliptical pupil.

The computer program Visual Optics Laboratory (VOL-Pro, version 7.30, Sarver & Associates, Inc., Carbondale, Illinois) was used to predict the peripheral aberrations to be expected in a typical human eye. For this purpose we used Atchison's myopic model eye²² with refraction-dependent parameters as the optical model.

There are many ways to define image quality (e.g. pupil plane metrics and image plane metrics^{43–45}) which are computable from data measured by aberrometer. Previous studies have reported that visual Strehl ratio (VSOTF, the contrast-sensitivity-weighted OTF divided by contrast-sensitivity-weighted OTF for diffraction limited optics³⁹) is highly correlated with logMAR visual acuity.⁴⁵ Hence, we chose VSOTF as the preferred metric to determine image quality on the retina in this study.

RESULTS

Variation Of Higher-Order Aberrations with Visual Field Eccentricity

Aberrations of the naked eye across the visual field are the baseline data for studying the effects of contact lenses. The RMS wavefront error of the higher-order modes increased with eccentricity as shown by the solid dark bars of Fig. 1. Most of this growth in RMS with eccentricity is due to changes in the 3rd- and 4th-order modes. By comparison, the 5th- and 6th-order aberrations change little across the visual field.

As expected for the horizontal visual field, horizontal coma (Z_3^1) is the major component of the 3rd-order aberration that increases in the peripheral visual field (Figure 2). Changes of Z_3^1 have a linear dependence on eccentricity, which confirms previous reports.^{41, 46} Horizontal trefoil (Z_3^3) also grows linearly with eccentricity, but at a slower rate. By comparison, vertical coma (Z_3^{-1}) and vertical trefoil (Z_3^{-3}) vary little across the horizontal visual field.

The nasal-temporal asymmetry of refractive error is thought to be due to angle alpha between the visual axis and the eye's optical axis.^{47, 48} Our previous study⁴¹ demonstrated that curvature of field and peripheral astigmatism are symmetric about an axis lying 5° temporal (negative visual field angle in figures) from the primary line-of-sight. Figure 1 shows that HOA RMS is also symmetric about this same axis, as are horizontal coma (Z_3^1) (Fig. 2) and spherical aberration (Z_4^0) (Fig. 3). Thus our results confirm earlier findings that the naked eye's optical axis is close to 5° temporal from the primary line-of-sight. To better reveal this symmetry, all subsequent figures show results for eccentricities relative to an optical axis located 5° temporal to the primary line-of-sight.

Table 1 shows that the contribution of Z_3^1 to the overall 3rd-order aberration increased from 15% in the optical axis of eye (which is approximately 5° in the temporal visual field) to 75% in the nasal and temporal 25° (relative to the optical axis of the eye). Horizontal trefoil (Z_3^3) contributes around 20% of the total 3rd-order aberration in the 25° periphery. Vertical coma (Z_3^{-1}) and trefoil (Z_3^{-3}) only contribute a small part to the overall 3rd-order aberration (less than 5%).

Spherical aberration (Z_4^0) is the major contributor to the change of 4th-order aberration RMS across the horizontal visual field. Our data show that spherical aberration (Z_4^0) is slightly positive in the fovea (0.18 μm), which is consistent with previous studies,^{1, 2, 49, 50} and increases following a quadratic function into the periphery.⁴⁶ The magnitude of Z_4^0 at 25° eccentricity is more than double the foveal value. Secondary astigmatism (Z_4^2) also increases with increasing visual field eccentricity, but none of the other 4th-order Zernike coefficients vary significantly across the horizontal visual field (Figure 3). Spherical aberration (Z_4^0) accounts for a higher percentage of overall 4th-order aberration in the peripheral field compared to the central field. At 25° eccentricity, about 65% of the 4th-order RMS is contributed by spherical aberration and 20% of the 4th-order RMS is due to the secondary astigmatism (Z_4^2) (Table 2).

Effect of Contact Lens Correction on Ocular Higher-Order Aberrations

Correction of the eye with contact lenses caused total higher-order aberration RMS to increase in the periphery, especially in the temporal visual field (Figure 4). This increase was greater for RGP lenses than for SCL ($p < 0.01$, non-parametric sign test⁵¹). However, 3rd-order RMS decreased across the horizontal visual field after contact lens correction. This reduction in wavefront error was greater for SCLs than for RGP lenses ($p < 0.01$, non-parametric sign test) (Figure 5A). Most of this change in 3rd order aberrations was due to correction of the eye's coma. The SCL reduced coma to less than 0.2 microns at all eccentricities (Fig. 5B). By comparison, the RGP lenses over-corrected ocular coma, resulting in coma levels that were nearly as large as for the naked eye, but with opposite sign. As a result, the total 3rd-order RMS for the RGP correction was only slightly less than for the naked eye. Figure 5 shows averaged data of 9 subjects in the study. Examination of the data in individual eyes confirmed that most eyes have less coma after both SCLs and RGP lens correction.

Unlike the case for 3rd-order aberrations, contact lens correction of the eye increased 4th-order aberrations across the horizontal visual field. This increase was greater for RGP lenses

than for SCLs ($p < 0.01$, non-parametric sign test) (Figure 6A). These changes brought about by the contact lens were due primarily to increases spherical aberration which was offset slightly by decreases in secondary astigmatism (Figure 6B).

Contact lenses increase 5th- and 6th-order aberrations, more so for RGP than for SCL lenses (Figure 7A & 7B).

Peripheral Image Quality with and without Contact Lens Correction

Image quality was assessed with the VSOTF metric^{44, 45} for the complete wavefront aberration (including 2nd order aberrations) measured over the full entrance pupil of each eye. When foveal refractive error is corrected with either SCL or RGP lenses, image quality improves greatly across the visual field mainly due to a reduction in 2nd order aberrations but nevertheless declines gradually from center to periphery as shown in Fig. 8. To reveal the effects of HOA we compare those results with image quality for the uncorrected eye viewing an extended target of constant vergence located at the foveal far-point (dark bars in Fig. 8). At every eccentricity tested, RGP lens correction provided superior image quality compared to the naked eye viewing a target with vergence that matches the foveal far point. This superiority was statistically significant ($p < 0.01$, non-parametric sign test) despite large variation between subjects. Image quality for SCL correction was worse than for the naked eye condition at all eccentricities, especially at larger eccentricities.

DISCUSSION

Our results show that 3rd- and 4th-order aberrations RMS increase away from center, which is consistent with what Navarro reported in 1998.⁵² 5th- and 6th-order aberration RMS varies in smaller range across the horizontal visual field. Among the 3rd-order and 4th-order aberrations, horizontal coma (Z_3^1) and spherical aberrations (Z_4^0), respectively, are the major components to contribute for the increasing of RMS to the periphery. Changes of horizontal coma (Z_3^1) have linear dependence on visual field angle. Changes of spherical aberration (Z_4^0) and secondary astigmatism (Z_4^2) have quadratic dependence on visual field angle. These changes are shown in our results and also predicted by Seidel theory.⁴⁶

Our companion paper⁴¹ reported that contact lenses partially or even over correct the hyperopic peripheral field curvature in myopic eyes and RGP lenses show an overall smaller sphero-cylindrical image blur on the retina across the horizontal visual field. Results in this paper demonstrated that contact lenses increase most HOA except 3rd-order aberrations. RGP lenses have more effect on increasing HOA in off-axis viewing angle compared to SCLs. Artal et al. suggested that the human eye is an example of robust optical design and corneal aberrations are compensated by the internal optics.^{53, 54} Contact lenses may upset the balance between the cornea and internal optics, leaving the whole eye's HOA increased (Fig. 4).

To reveal the effects of HOA on peripheral image quality we considered the following hypothetical scenario. Suppose that an uncorrected myopic eye is viewing an extended target located at the foveal far-point so that the defocus component of the wavefront aberration is zero at the fovea. If target vergence remains constant across its extent, then retinal image quality will be determined by the combination of peripheral relative defocus, peripheral astigmatism, and peripheral HOA. The wavefront aberration for this scenario is the measured naked eye, corrected for target vergence (approximately) by subtracting foveal C_2^0 from C_2^0 values in the peripheral visual field. Image quality in that scenario is slightly inferior to the case of RGP correction but superior to the case of SCL correction. These differences exist everywhere in the visual field ($p < 0.01$) but might not reach clinical significance at some eccentricities (Fig. 8). It is possible that lens movement on the eye

might negate the relative superiority of image quality for RGP corrections. The visual benefit of potentially correcting peripheral HOA with contact lenses would be expected to be greater with improved correction of peripheral LOA. Consistent with previous studies,^{55–57} large between-subject variation was noticed in this study and this may impose hurdles for clinicians and CLs manufacturers to manipulate vision correction in periphery.

To evaluate the trends revealed by our experimental data, we used VOL software to calculate the expected aberrations across the visual field for Atchison's myopic model eye. We used –3D myopic eye model with 3.2mm pupil diameter during the calculation and up to 16° of eccentricity (the maximum permitted by VOL). A –3D RGP lens with spherical front and back surface design was used to build our VOL model. (Modeling SCLs is more difficult since soft lenses conform to the corneal shape.). These theoretical expectations, shown in Figure 9, indicate a general trend that is consistent with our findings. Correction of the myopic eye with an RGP lens increases all higher-order aberrations across the visual field except 3rd-order aberration. Moreover, RGP lenses reduce the magnitude of horizontal coma (Z_3^1) and reverse the sign of the slope for the linear relationship between coma and eccentricity. Since the purpose of the theoretical modeling was to identify qualitative trends, we did not expect quantitative agreement with experimental data. A variety of factors preclude close quantitative comparisons of clinical measurements with a schematic eye model (e.g., paraxial model vs. large-pupil human eyes, individual variation in corneal curvatures and other model parameters, alignment of the CL to the eye). Nevertheless, our modeling confirmed that the observed trends of how CLs affect peripheral aberrations are consistent with optical theory.

Our experimental results and theoretical predictions indicate that, with the exception of coma, HOA in the periphery increase after CLs correction. At the same time, second order aberrations decrease throughout the visual field as a side-benefit to correcting the central field. For the myopic eye, the benefit gained by reducing defocus will greatly outweigh the minor increase in astigmatism⁴¹ and HOA (Fig. 1). Nevertheless, peripheral image quality could be even better if the contact lens did not increase HOA beyond the levels present in the naked eye. To determine how much improvement in peripheral image quality would be gained by a contact lens that fully corrected HOA, we computed VSOTF assuming the higher-order Zernike coefficients are zero everywhere in the visual field. This leaves the second-order aberrations (field curvature and oblique astigmatism) as the only limiting factors. Cheng et al⁴⁵ reported that changing VSOTF by 0.1 would be expected to reduce foveal MAR by 0.1 log unit, which is clinically significant. Figure 10 shows a small but constant improvement of image quality across the visual field (less than 0.01 in the periphery to 0.07 centrally) gained by fully correcting HOA with either SCLs or RGP lenses. Aberration-free RGP correction will yield a greater improvement of image quality (compared to SCLs correction) ($p = 0.02$, non-parametric sign test) because RGP lenses produce more HOA (Figs. 6, 7). Although these aberration-free CLs produced statistically significant improvement of image quality, this improvement may not be clinically significant based on our standard (0.1 change of VSOTF). However, we remain optimistic. If contact lenses did a better job of correcting lower-order aberrations across the visual field, then the visual benefit of also correcting HOA would be even greater than is indicated in Fig. 10.

Figure 10 indicated that HOA have slightly greater effect on image quality (0.01 –0.02 improvement on VSOTF) in eyes corrected with RGP lens compared to SCLs. We also conclude from Figure 10 that HOA have a greater effect on image quality in the central visual field than in the periphery in the corrected eye because when the HOA are eliminated, image quality improves more in the central field. To better understand this effect of HOA on overall image quality, we randomly choose a measured data set in a 20° periphery from an

individual eye. By gradually optimizing each Zernike coefficients (set Z_c to zero), VSOTF calculation was repeated. Data are reported as case 1 in Figure 11. Image quality increased dramatically after removing the 5th Zernike mode, which is Z_2^0 (defocus term). Image quality improved more after removing Z_2^2 (With-The-Rule and Against-The-Rule astigmatisms). Image quality gradually improves with sequentially removing other higher-order Zernike terms. Two big improvements of image quality are noticed by removing Z_3^1 and Z_4^0 , which suggest that horizontal coma (Z_3^1) and spherical aberration (Z_4^0) have the major effects inhibiting image quality. In case 2, we keep the 2nd-order aberration in the eye but gradually remove each Zernike modes starting from 7th (Z_3^{-3}). Image quality also keeps improving as we remove those higher-order Zernike terms, but not as dramatically as in Case 1. By omitting HOA in case 1, Strehl Ratio increases about 0.4 but in case 2, omitting HOA Strehl Ratio increases about 0.2. This analysis demonstrates that when initial image quality of an eye is good, HOA will have a powerful effect on image quality. Conversely, when image quality is poor originally, then the additional effect of higher-order aberrations will be minor.

In conclusion, contact lens increases higher-order aberrations in the peripheral visual field except 3rd-order Zernike terms. RGP lenses slightly improve peripheral image quality for objects located at the foveal far point. Increased HOA after contact lens correction reduces image quality by an amount that depends on the eye's initial image quality. If the eye has good image quality initially, changes in HOA have a relatively large effect on image quality. But if the eye has poor image quality initially, HOA will have relatively small effect on image quality. These results suggest contact lens designer and manufacturers should aim to improve the capabilities of contact lens for correcting HOA while simultaneously providing best sphero-cylinder correction for the eye across the visual field.

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Figure 1.

Ocular HOA RMS changes as functions of eccentricity relative to fovea (negative X-axis indicates temporal visual field (T) and positive X-axis indicates nasal visual field (N), these sign conventions will be used in the following figures as well). Each bar indicates the mean value of RMS in microns of all the subjects. Error bars indicate standard error of the mean of the data point for all the subjects.

Figure 2. Changes of 3rd-order Zernike coefficients terms with increasing of visual field eccentricities. Open symbols indicate horizontal modes, closed symbols indicate vertical modes. Circles represent coma and triangles represent trefoil, respectively. Each symbol indicates the averaged value of Zernike coefficients value of all our experimental subjects. Error bars represent standard error of the mean of all our subjects. Negative X axis indicates temporal visual field (T) and positive X axis indicate nasal visual field (N).

Figure 3. Changes of 4th-order Zernike coefficients terms with increasing of visual field eccentricities. Each symbol indicates the averaged value of Zernike coefficients value of all our experimental subjects. Error bars represent standard error of the mean of all our subjects.

Figure 4.

Changes in total HOA RMS with SCLs and RGP lens correction compared to no lens condition. Symbols indicate total HOA RMS (relative to optical axis) with correction minus total HOA RMS (relative to optical axis) without correction. Error bars indicates standard error of the mean of experimental subjects.

Figure 5.

(A) Changes in 3rd-order aberration RMS with SCLs and RGP lens correction compared to no lens condition; (B) Relative magnitude of horizontal coma (subtract C_3^1 on-axis from C_3^1 off-axis) with and without contact lens correction across visual field. Symbols in A indicate the changes of 3rd-order RMS, computed as RMS relative to optical axis with correction - RMS relative to optical axis without correction. Symbols in B represent mean value of C_3^1 relative to optical axis of all subjects before and after contact lens correction. Error bars in both figures indicate standard error of the mean of experimental subjects.

Figure 6.

(A) Changes in 4th-order aberration RMS after CL correction across visual field (4th-order RMS relative to optical axis after CL correction – 4th-order RMS relative to optical axis in uncorrected eye). (B) Changes in C_4^0 and C_4^2 relative to optical axis after CL correction with visual field eccentricity (C_4^0 or C_4^2 after CL correction – C_4^0 or C_4^2 in uncorrected eye). In B, open symbols indicate changes after RGP correction, closed symbols indicate changes after SCLs correction. Circles represent C_4^0 and triangles represent C_4^2 , respectively. Symbols indicate the averaged changes of RMS or coefficients value relative to optical axis of all subjects and error bars show standard error of the mean in the subjects.

Figure 7.

(A) Changes in 5th-order aberration RMS after CLs correction across visual field (5th-order RMS relative to optical axis after CLs correction – 5th-order RMS relative to optical axis in uncorrected eye). (B) Changes in 6th-order aberration RMS after CLs correction across visual field (6th-order RMS relative to optical axis after CLs correction – 6th-order RMS relative to optical axis in uncorrected eye). Symbols represent averaged data of changed RMS relative to optical axis of all subjects and error bars indicate standard error of the mean of these changes in all subjects.

Figure 8. VSOTF changes across visual field eccentricities in uncorrected eye viewing a target with vergence that matches the foveal far point (black bars) and in eyes corrected by soft (gray bars) or rigid (open bars) contact lenses. Bar height indicates the mean value of VSOTF of all subjects and error bars indicate standard error of the mean of averaged VSOTF in the subjects.

Figure 9.

VOL modeling of changes of 3rd- to 5th-order aberration RMS and C_3^1 , C_4^0 , C_4^2 coefficients with increasing of off-axis viewing angle. Note that ordinates have different scales for different aberrations. Sixth order aberration RMS are not shown because they are very small across the visual field. Open circles indicate data points without correction and open triangle symbols represent data with contact lens (RGP lenses) correction.

Figure 10. Changes in VSOTF after eliminating HOA (set all HOA equal to zeros) in SCLs and RGP lenses corrected eyes. VSOTF values are averaged from 9 subjects. Error bars indicate standard error of the mean of averaged VSOTF changes in the subjects.

Figure 11.

VSOTF changes as Zernike modes are gradually removed from calculation in a single subject. Case 1 indicates removing Zernike modes start from Z_{-2}^{-2} . Case 2 indicates removing Zernike modes start from Z_3^{-3} . Error bars are the mean of standard error of three measurements.

Table 1

Contributions of each 3rd-order Zernike Coefficients to the total 3rd-order RMS.

	Temporal 25°	Optical Axis	Nasal 25°
	Coefficients in μm (% to total 3 rd RMS)	Coefficients in μm (% to total 3 rd RMS)	Coefficients in μm (% to total 3 rd RMS)
Z_3^{-3}	−0.012 (1.93%)	0.055 (33.72%)	−0.007 (1.07%)
Z_3^{-1}	−0.003 (0.44%)	−0.038 (23.04%)	0.012 (1.81%)
Z_3^1	−0.455 (73.93%)	0.024 (14.64%)	0.519 (79.23%)
Z_3^3	−0.146 (23.69%)	−0.047 (28.60%)	0.117 (17.87%)

Table 2

Contributions of each 4th-order Zernike Coefficients to the total 4th-order RMS.

	Temporal 25°	Optical Axis	Nasal 25°
	Coefficients in μm (% to total 4 th RMS)	Coefficients in μm (% to total 4 th RMS)	Coefficients in μm (% to total 4 th RMS)
Z_4^{-4}	-0.028(4.71%)	-0.065(16.40%)	0.026(5.11%)
Z_4^{-2}	0.008(1.40%)	0.041 (10.34%)	-0.009(1.77%)
Z_4^0	0.361 (60.72%)	0.160(40.19%)	0.344 (67.58%)
Z_4^2	0.117(19.70%)	0.031 (7.79%)	0.084(16.50%)
Z_4^4	0.080(13.47%)	0.101 (25.29%)	0.046 (9.04%)