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Ocular Aberrations and Image Quality, Contact Lens and MYOPIA Progression

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1. Introduction

The eye as an optical instrument is imperfect with defocus, astigmatism and higher-order aberrations being common. The image formed on the retina is affected by these optical deficiencies. Refractive errors (myopia, hyperopia and astigmatism) are the most common ocular aberrations, and they are called lower-order aberrations. There are numerous higher-order aberrations, of which spherical aberration and coma are most of clinical interest. Refractive errors have been studied for many years and clinicians devote themselves to correct these focusing errors.

Compared to the efforts to understand and optimize the central vision, peripheral vision is not well understood. However, peripheral vision is important for motion and pattern detection and fundus imaging. Also, interest in studying the off-axis optical performance and image quality of humane eye has increased dramatically in recent years because the previous studies suggest a possibility that off-axis aberrations in human eye is important for the development of central refractive error.

Given the hypothesis that off-axis aberrations and image quality may affect central refractive error development, it is important to understand how ordinary ophthalmic lenses, which are used to correct foveal vision, influence the peripheral optics of human eye.

In this chapter, we will describe and discuss the following six major topics: 1) control of ocular growth, 2) axial ocular aberrations, 3) off-axis aberrations, 4) contact lens and myopia progression, 5) peripheral refractions and contact lens correction, and 6) peripheral image quality and contact lens correction.

2. Control of ocular growth

Animal studies have demonstrated that the eyes growth is controlled by local retina mechanism. [1-3] Local retinal mechanism refers to a condition that local retina could minimize the image degradation on the corresponding retinal location by changing the axial eye growth rate. [4] The homeostatic control signals of the eyes growth try to keep the image sharply focused on the retina ("grow to clarity" model). [5] If the eye is in myopic status, the image of a distant object falls in front of the retina and if the eye is hyperopic, the image falls behind the retina. These two situations are simulated in Fig. 1A, inserting a positive lens put the image in front of the retina (myopic focus) and negative lens focus the image behind the retina (hyperopic focus). By increasing the thickness of choroids or slowing the rate of eye's elongation, the eye can grow to counteract the effect of the lens, regaining a sharp focus (for small amount of myopic defocus). For hyperopic defocus, the choroids will become thinning and the rate of eye's elongation will increase in order to focus the image on retina again (Fig. 1B). [6-8] These were proved by previous animal studies. [9-13] For example, animals, like birds, consistently experience near objects in their inferior visual field have longer superior ocular length. [14, 15]
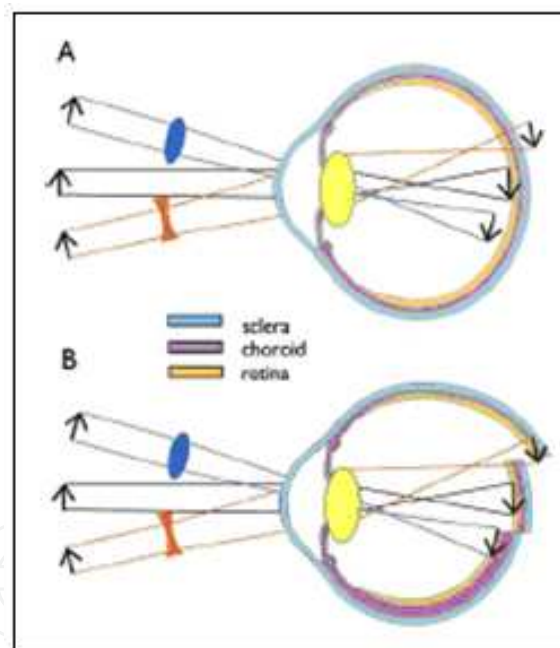

Figure 1. Ocular Compensation for lens-Induced Defocus

a. A positive lens (blue, convex) causes the image to form in front of the retina (myopic defocus), whereas a negative lens (red, concave) pushes the image plane behind the retina (hyperopic defocus). With no lens (black rays), the image of a distant objects is focused on the retina.

b. The eye compensates for positive lenses by slowing its rate of elongation and by thickening the choroid, pushing the retina forward toward the image plane. It compensates of

negative lenses by increasing the rate of elongation and thinning the choroid, pulling the retina back toward the image plane. The emmetropic eye is intermediate in length and in choroid thickness. (Figure and legend from [1])

As a development of local retina mechanism model in animal study, data from human beings also suggested that peripheral refractive error can influence the ocular growth. [16-19] For example, young pilots that had relatively hyperopic refractive status in both horizontal and vertical meridian, which potentially contributes to the eye's elongation, were more likely to develop adult-onset myopia than those who showed myopic refractive status at least in one meridian. [16] More recently, Smith and colleagues [20] have tested the hypothesis that the peripheral visual experiences contribute for the ocular growth and central refractive development in primates. Their study provided strong evidence that the peripheral retinal mechanism can influence the refractive development at the fovea and this, most likely, also happens in human beings.

3. Axial ocular aberration

Aberrations are classified as monochromatic and chromatic aberrations. Chromatic aberrations occur when light source has multi-wavelength components. Monochromatic aberrations occur when only one wavelength light source is refracted. The aberration discussed in this chapter is monochromatic aberration.

3.1. Representation of aberration

It is useful to understand wavefront and wavefront aberration before we discuss the measurement and representation of aberration. A wavefront is a surface which is orthogonal to light rays. The wavefront aberration is the distance, in optical path length (product of the refractive index and path length), from the reference plane to wavefront plane at the exit pupil (Figure 2).
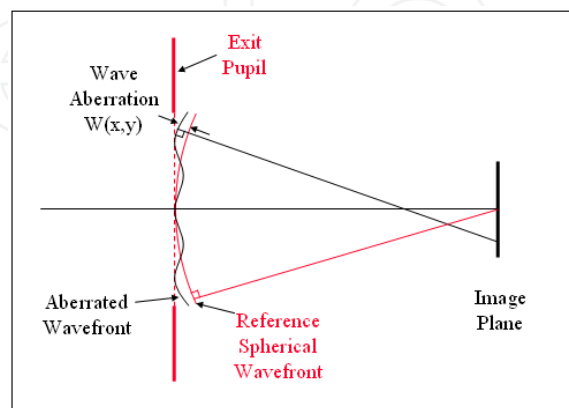

Figure 2. The concept of wavefront aberration: wavefront aberration is the departure of the measured wavefront from the ideal spherical wavefront at the exit pupil.

There are different ways to represent wavefront aberrations such as Taylor series and Zernike polynomials. The Taylor series are rarely used these days since each individual term are not orthonormal. [21] People usually use Zernike series which were recommended by Optical Society of America to describe the eye's wavefront error (Figure 3 & Table 1). [22]
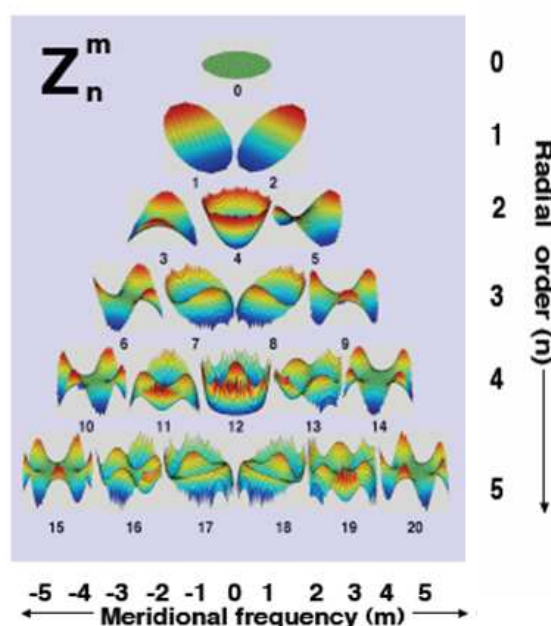

Figure 3. Zernike polynomials: Each row is a radial order. Each column is a meridional frequency. Each function is defined over the circular domain of the pupil and is mathematically orthogonal to all other functions in the table.

The normalized Zernike polynomial has two major advantages when applied to quantify the optical aberrations. First, the magnitude of the Zernike coefficient represents the wavefront error in that mode and usually given in the unit micrometers (μm). Second, in the Zernike series, each mode is orthogonal to the other mode, so the coefficients are independent of each other. This will allow us to manipulate each mode individually. RMS (root mean square) error is widely used to indicate the human eyes' wavefront error in each mode or combined modes. RMS is defined as

$$RMS = \sqrt{\sum_{n>1,m} (C_n^m)^2} \tag{1}$$

First and second order aberrations are regarded as lower-order aberrations. 1st-order Zernike terms are tilts which do not cause image blur therefore are usually ignored. Traditional refractive errors refer to 2nd-order Zernike terms. The relationship between 2nd-order Zernike coefficients and sphero-cylindrical components M, J_0, J_{45} (M: the spherical equivalent, J_0: with-the-rule (WTR) and against-the-rule (ATR) astigmatism, J_{45}: oblique astigmatism with axes at 45 deg and 135 deg) is given by the following equations. [23]

mode	order	frequency	
j	n	m	$Z_n^m(\rho,\theta)$
0	0	0	1
1	1	-1	$2\rho\sin(\theta)$
2	1	1	$2\rho\cos(\theta)$
3	2	-2	$\sqrt{6}\rho^2\sin(2\theta)$
4	2	0	$\sqrt{3}(2\rho^2-1)$
5	2	2	$\sqrt{6}\rho^2\cos(2\theta)$
6	3	-3	$\sqrt{8}\rho^3\sin(3\theta)$
7	3	-1	$\sqrt{8}(3\rho^3-2\rho)\sin(\theta)$
8	3	1	$\sqrt{8}(3\rho^3-2\rho)\cos(\theta)$
9	3	3	$\sqrt{8}\rho^3\cos(3\theta)$
10	4	-4	$\sqrt{10}\rho^4\sin(4\theta)$
11	4	-2	$\sqrt{10}(4\rho^4-3\rho^2)\sin(2\theta)$
12	4	0	$\sqrt{5}(6\rho^4-6\rho^2+1)$
13	4	2	$\sqrt{10}(4\rho^4-3\rho^2)\cos(2\theta)$
14	4	4	$\sqrt{10}\rho^4\cos(4\theta)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Table 1. List of Zernike Polynomials

$$M = \frac{-4\sqrt{3}}{r^2}C_2^0$$

$$J_0 = \frac{-2\sqrt{6}}{r^2}C_2^2 \tag{2}$$

$$J_{45} = \frac{-2\sqrt{6}}{r^2}C_2^{-2}$$

Where C_{20}, C_{22}, C_{2-2} are Zernike coefficients for defocus, WTR/ATR astigmatism and oblique astigmatism terms, and r is pupil radius. We can also use the following equation to convert rectangular Fourier form (M, J_0, J_{45}) to conventional clinical negative-cylinder form. [24]

$$S = M + \sqrt{J_0^2 + J_{45}^2}$$

$$C = -2\sqrt{J_0^2 + J_{45}^2} \tag{3}$$

$$\alpha = \frac{1}{2}\tan^{-1}(J_{45}/J_0)$$

Start from 3rd order Zernike terms, aberrations are referred as higher-order aberrations. Coma ($C_{3\pm1}$) and spherical aberration (C_{40}) are the most important higher-order aberrations since they present in higher amounts than the other higher-order aberrations in the population. [25, 26]

3.2. Measurement of aberrations

As a development of autorefractors, aberration measuring instruments bear the same principle (Scheiner disc principle) which illustrated in Figure 4. [27, 28] Aberrations can be measured by "into-the-eye" or "out-of-the-eye" aberrometry technique. [28, 29] "Into-the-eye" aberrometry means an image is formed on the retina and re-imaged out of the eye for analysis, like laser ray tracing and Tscherning aberrometer. "Out-of-the-eye" aberrometry refers to an instrument which project a narrow beam into the eye and trace the rays from the retina out of the eye, like Hartmann-Shack wavefront sensor. [28] Aberrometer measure aberrations either sequentially or simultaneously. Sequential aberrometry, like laser ray tracing, measures aberration in one location of the pupil once a time but simultaneous aberrometer (Hartman-Shack wavefront aberrometer) can measure aberration at multiple locations of the pupil at the same time.
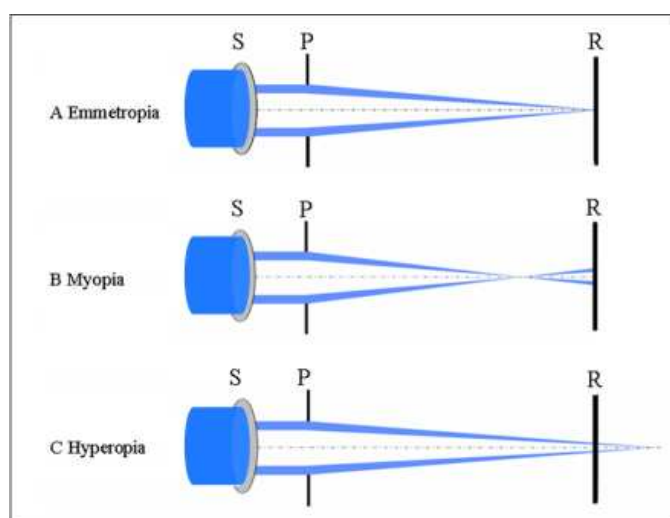

Figure 4. Scheiner disc principle: Light comes from a distant object reduce to two small bundles of light by two pin-holes on Scheiner disc. These two rays focus to be a single image on the retina if the eye is emmetropia (Figure 4 a). Double images will be sensed if the eye is myopia or hyperopia (Figure 4 b&c). By adjusting the position of the object until on image is seen, the far point and refractive error of the patient's eye can be determined. S: Scheiner disc; P: Pupil; R: Retina

Most commercial aberrometers use Hartmann-Shack wavefront sensor. Hartmann-Shack technology can be tracked back to early 20th century when Hartmann test was used to measure aberration of optical system. [30, 31] Shack and Platt modified Hartmann technique to invent the Hartmann-Shack aberrometer. [32] This technique was originally developed by astronomers for improving the image quality of the stars and satellites and Liang et al. [33] adapted it to measure conventional refractive errors as well as higher-order aberrations of the eyes. The principle of operation of the Hartmann-Shack aberrometer is shown in Figure 5.
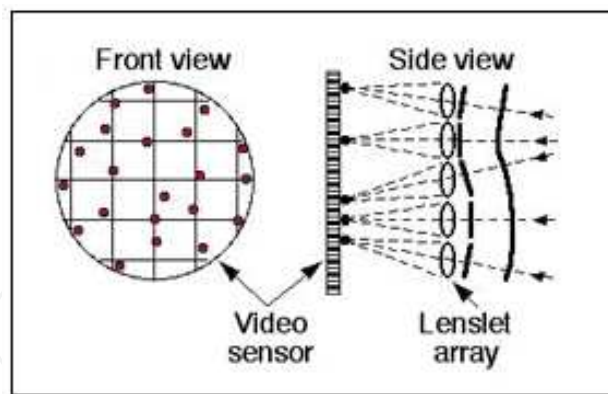
Figure 5. Principle of the Hartmann-Shack (HS) wavefront sensor. HS sensor subdivides the wavefront into hundred small beams which are focused on to a CCD video sensor by an array of small lenses. The displacement of each image relative to the grid of optical axes is determined by the local slope of the wavefront in x-and y-direction at the face of the corresponding lenslet. [Adapted from Thibos [34]]

The critical part of Hartmann-Shack wavefront sensor is a micro-lenslet array. A CCD video sensor is placed in one focal length of those small lenses behind the lenslet array. The reflected wavefront of light emerging from the eye will be partitioned to hundred smaller wavefront and will be focused on the CCD sensor. If the measured eye is a perfect optical system, the wavefront emerging from the eye will be a plane and will be focused perfectly on the intersections of the grids. In the real situation, the aberrated wavefront coming back from the eye will be focused by each lenslet on CCD sensor with displacement corresponding to lenslet axis. The local slopes of the wavefront can be deduced from this displacement.

Hartmann-Shack aberrometer have been widely used to measure aberrations in different area of clinical research [34-40] due to its fast measuring and less affected by scattering of light compared to most other aberrometers. [41] Hartmann-Shack wavefront aberrometer has been reported as a robust and reliable instrument to measure both lower and higher order aberrations. [34, 42, 43]

4. Off-axis aberration

While previous studies concentrated on foveal aberrations, investigations of off-axis (peripheral) vision increased dramatically in recent years because the quality of off-axis optics is important for retina imaging, motion and orientation detection, and development of refractive error. [20, 44-48]

4.1. Measurement of Off-axis aberration

Little is known about off-axis wavefront aberrations and image quality in the eccentric visual fields, for which most studies only reported the changes of defocus and astigmatism in the peripheral visual angle. [16, 46, 47, 49-51] Different techniques, such as retinoscopy, [46, 49, 51, 52] subjective refraction, [47, 50],photorefraction [53] and autorefraction, [54] were used to measure these lower-order aberrations in the peripheral visual field.

The published studies on peripheral refraction [16, 17, 28, 53, 55-58] suggested that hyperopes had relative less hyperopic error in the periphery, while myopes usually had relative less myopic error in periphery. These experimental data was consistent with the previous predictions made by Charman and Jennings [59] and Dunne et al. [60, 61] which used simple models with ray tracing technique on the schematic eye.

In 1998, Navarro et al. first measured higher-order aberrations in four naked eyes using laser ray-tracing method and described aberrations using Zernike polynomials. [62] They measured nasal visual field only and reported that despite large variation between subjects, the four subjects showed the same pattern of the change of the aberrations across the visual field. They found both 3rd-and 4_{th}-order aberrations increasing from center to periphery. Atchison and Scott were the first to use Shack-Hartmann wavefront aberrometer to measure off-axis higher-order aberrations in human eye. [63] They measured aberrations both in nasal and temporal visual field up to 40_{o}. Like Navarro's study, Atchison's data also showed large between-subject variability. They reported that 3rd-order aberration increased to both nasal and temporal visual field and with nasal-temporal asymmetry. Unlike Navarro's study, they didn't report the large change of 4_{th}-order aberration across the horizontal visual field. Both these two studies only recruited small number of subjects.

In the previous studies, [62-67] researchers didn't attempt to quantify the image quality in the peripheral visual field. Most researchers talked about the peripheral image quality, speculated that off-axis IQ would drop fast and become worse based on the measurements of peripheral refraction (defocus and astigmatism). They neglected the complex interaction between these lower-order and the higher-order aberrations in eyes. [68] In order to investigate the off-axis image quality, to study the interaction between lower-order aberrations and higher-order aberrations in the large visual angle and to study the potential contributions of the off-axis image quality to the whole eyes refractive development, the first step is to measure the monochromatic aberrations in the peripheral visual field accurately.

4.2. Peripheral vision and development of refractive error

The rationale that peripheral refraction can influence the development of refractive error is pointed out by Wallman [1] that if the peripheral retina is relatively hyperopic, this relatively hyperopic defocus will cause the elongation of the eyeball no matter what the foveal refractive status is. As mentioned above, the homeostatic signals from the hyperopic periphery will guide the eye to elongate. If the fovea retina is emmetropic or myopic, the homeostatic signals from the central retina will direct the eye to elongate less. These two signals, from central retina and from the peripheral retina, will try to keep balance. Although the neurons density is higher in the central than in the peripheral retina, considering the total area of the central retina is quite small, the homeostatic signals from peripheral retina directing the eye to elongate more will be stronger than the signals from central retina that directing the eye to elongate less if these signals have spatial summation. If the larger area of the retina become elongated surrounding the fovea area, the mechanical constrains in eye growth will also make the fovea axially elongated. [1] This mechanism has been hypothesized by several studies. [53, 58, 69]

The critical step to understand the above mechanism is that the peripheral retina has the capacity to detect the changes of image quality which are produced by the off-axis aberrations.

[47, 70, 71] Peripheral vision is limited by two factors: the optical image quality and the neurons density in the periphery. It is already known that in large visual angles, the oblique astigmatism increases dramatically. However, these refractive errors can be corrected by ordinary ophthalmic lenses. There are other higher-order aberrations such as coma and spherical aberrations in the off-axis visual field which can also deteriorate the image quality but are difficult to correct. [72] The neurons density (including cones and ganglion cells) is at maximum near the fovea and drops quickly in the periphery. [73] This neurons density constitutes an upper limit of the visual acuity at higher retinal field angles when the off-axis optics is corrected.

The resolution acuity becomes worse with the increasing of the retina eccentricity, but the detection acuity remains high at large eccentricities given the peripheral optics are well corrected. [71, 74] Detection acuity is significantly influenced by the optical defocus and is lower when the retina image is formed by the eye's natural optics, these suggest that the detection acuity is optically limited. [74, 75] But after correct the major off-axis aberrations (defocus and astigmatism), the detection acuity becomes quite good in the peripheral visual field. [70, 76]

Besides evidences supported by other human studies, [16, 17, 19, 77] Smith and colleagues [20] provided further evidence that visual experience in peripheral retina can influence the refractive development at the fovea. And as a development, other studies made a hypothesis that high level of aberrations will guide ocular elongation by degradation of the retinal image. [78-82] Growth of the eye tends to minimize the image blur on the most part of the retina (known as "grow to clarity" model). [5] Thus peripheral vision is closely related with development of central refractive error.

5. Contact lens and myopia progression

Contact lenses are widely used treatments for refractive errors. They had long been used as an optical correction since their introduction by Eugen Fick in 1888. [83] A large number of studies investigated the effect of different types of contact lenses (silicone acrylate contact lenses, hydrophilic contact lenses, hydrogel lenses) on the progression of myopia had been done. [84-90] Though most of the studies had small sample size or were not randomized, they did suggest that wearing soft contact lenses induced increasing in myopia progression. [84, 91, 92] Another large sample size, randomized study done by Horner et al. suggested that there were no significant different in the rate of myopia progression between the children who wore SCLs and spectacles. [93]

Hard contact lenses have longer history than the SCLs. PMMA (polymethyl methacrylate) hard contact lenses were widely prescribed in the clinic although they have side effects caused by low oxygen permeability. After 1970', Rigid-Gas-Permeable (RGP) lens becomes popular. These lenses have higher oxygen permeability than soft contact lens, clinically proved to be a suitable and safer alternative for correcting refractive error. [89] In a three years study, 100 children with myopia were fitted with RGP and compared with control group who wore spectacles, significant reduction of myopia progression was found. [94] Another study also reported a similar results. [95]

Although in 2003, a larger randomized clinical trial of rigid contact lenses conducted in Singapore Children didn't report significant difference of myopia progression between RGP wearers and spectacles wearers, [96] the more recent CLAMP (Contact Lens and Myopia Progression) study [18] has shown that RGP produced a significant slower rate of progression of myopia in children, although this was largely due to flattening of the cornea rather than slowing of axial elongation. [97]

No matter whether the SCLs or RGP lenses can slow the progression of myopia or not, all of the SCLs and RGP studies above tried to relate the lens' efficacy with the ocular physiological changes. No studies have examined the peripheral optical quality after these ophthalmic corrections although there were attempts to evaluate on-axis optical performance of these lenses. [39, 98] Since the peripheral vision is an important factor to contribute for the development of myopia, experimentally measure the monochromatic off-axis aberrations with these ophthalmic lenses on-eye is my proposed experiment and will discussed in detail in later chapters.

5.1. Contact lens and on-axis ocular aberration

The on-axis optical quality after wearing RGP lenses has been well studied both by theoretically calculation and experimental measurements. [99-101] It is widely accepted in clinic that RGP lenses provided the best optical performance for the central vision compared to SCLs and spectacles. RGP lens can smooth the irregularities of the corneal front surface with its rigidity and smooth lens surface. With the correction of moderate astigmatism by the tear lens between RGP and cornea, RGP lenses provide the best on-axis optical performance. Due to the conformity of SCLs, the corneal astigmatism and corneal irregularity will be preserved in some extent for the SCLs wearer (Fig. 6). Theoretically calculation of the on-axis aberrations of RGP lenses always ignores the interaction between the cornea and contact lenses, also without considering the contribution of inner components of the eye to the total optical aberrations. Only Hong et al. [100] and Dorronsoro et al. [98] have measured aberrations in subjects wearing RGP lenses, finding that RGP lenses provided lower aberrations than SCLs and spectacle lenses. They concluded that wearing RGP lenses can significantly reduce the ocular aberrations, not only defocus and astigmatism, but also higher-order aberrations.
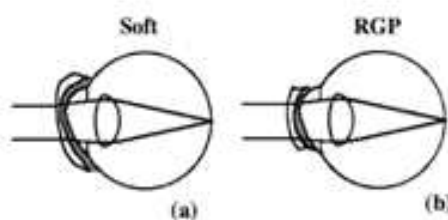

Figure 6. Schematic diagram of the eye with a) soft contact lens, b) rigid gas-permeable (RGP) contact lens. The shaded regions indicated the tear layer. Corneal distortions are exaggerated to illustrate the differences between different optical corrections. [Adapted from [39]]

5.2. Contact lens and off-axis aberrations

Since contact lens correct central refractive error by adding an appropriate compensating power across the entire eye, it will affect the peripheral vision as well while foveal refractive errors are corrected. And due to the potential role of peripheral vision in the development of central refractive error, it is possible that the ophthalmic corrective methods which only correct the central vision but ignoring peripheral image quality will be less successful for controlling myopia progression. Since the myopic eyes have a relative hyperopic periphery, correcting the central myopic will leave the periphery hyperopic (if the correcting lenses have the same power everywhere across the lens piece). The hyperopic periphery will continue to guide the elongation of the eye and the progression of myopia will not stop. Thus the contact lens correction which only corrects the central vision might actually have no effect or even increase the progression of myopia. However, we lack the knowledge of how contact lenses affect peripheral optics of the eye. Although knowledge of off-axis aberrations of CL in isolation is important to help understanding the effect of CLs on peripheral optics of the eye, [102] to obtain a definitive result of how the peripheral refractive error and image quality changes across the visual field with CLs correction requires that the CLs be worn by a human eye.

6. Peripheral refractions and contact lens correction

Multiple studies [53, 103-105] have shown that hyperopic and emmetropic eyes tend to have peripheral refractive errors that are myopic relative to the fovea. The image shell from a distant, extended object is therefore more curved than the retinal surface, resulting in an increasing amount of myopic blur at greater retinal eccentricities. In this chapter, we will refer to this condition as "myopic field curvature" or "relative peripheral myopia". By contrast, myopic eyes tend to have less myopia in the peripheral visual field than foveally. Most authors agree on this point for the horizontal field, but there is some controversy regarding the generality of the finding at the other meridian. [53, 54, 106] The image shell from a distant, extended object is less curved than the retinal surface in myopic eyes, resulting in a decreasing amount of myopic blur at greater retinal eccentricities. Thus, relative to foveal refractive error, the eye has an increasing amount of hyperopic blur at greater retinal eccentricities. In this chapter, we will refer to this condition as "hyperopic field curvature" or "relative peripheral hyperopia".

The rationale that peripheral refraction can influence the development of refractive error is that if the peripheral retina is relatively hyperopic, this relatively hyperopic defocus will cause the elongation of the eyeball no matter what the foveal refractive status is. As mentioned above, the homeostatic signals from the hyperopic periphery will guide the eye to elongate. If the fovea retina is emmetropic or myopic, the homeostatic signals from the central retina will direct the eye to elongate less. These two signals, from central retina and from the peripheral retina, will try to keep balance. Although the neurons density is higher in the central than in the peripheral retina, considering the total area of the central retina is quite small, the homeostatic signals from peripheral retina directing the eye to elongate more will be stronger than the signals from central retina that directing the eye to elongate less if these signals have spatial

summation. If the larger area of the retina become elongated surrounding the fovea area, the mechanical constrains in eye growth will also make the fovea axially elongated. This also demonstrated by the local retina mechanism. [58, 69, 107].

More recently, Smith and colleagues [108] have tested the hypothesis that the peripheral visual experiences contribute for the ocular growth and central refractive development in primates. Their study provided strong evidence that the peripheral retinal mechanism can influence the refractive development at the fovea and this, most likely, also happens in human beings.

6.1. Curvature of field and peripheral astigmatism for the naked eye

Consistent with most previous studies, emmetropic eyes showed myopic shift into the periphery (Fig.7 a & b) whereas myopic subjects showed relatively hyperopic shift (Fig.8 a & b). Greater myopia and higher astigmatism in the nasal visual field than in the temporal visual field were found in most of the subjects in the study (Fig.7, 8, 9, 10 & Fig.11). This asymmetry of the changes of M, J_0 and J_{45} across horizontal visual field has been noted in previous, large-scale studies of peripheral refraction. However, the larger error bar indicated that there were considerable differences occur among the subjects. (Within-subject variance was small as indicated from the Fig.7a and Fig.8a, but this might be due to the lack of necessary realignments of the instrument between the measurements in each visual angle position.) A more apparent hyperopic shift beyond 20 degree eccentricity was found (Fig.7). (Previous, Atchison et al. reported a subtle changes in refraction across the central 10º of the retina, with changes in M varying by up to half a diopter and with smaller changes in astigmatism [109].)
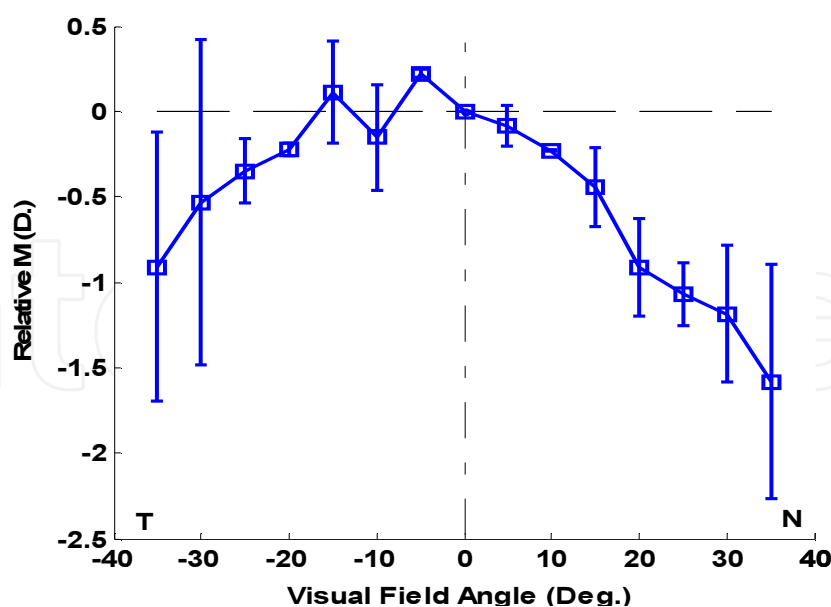

Figure 7. a) Spherical equivalent refractive error (M) relative to the fovea as a function of visual field angle for Sub.1 and Sub.2. Both of these two subjects are emmetropes. Symbols show the means and Error bar indicate the standard deviation of 5 repeated measurements. b) The mean value of Spherical equivalent (M) as a function of visual field angle for the two emmetropes. Error bar indicate the standard deviation of the two emmetropic subjects.
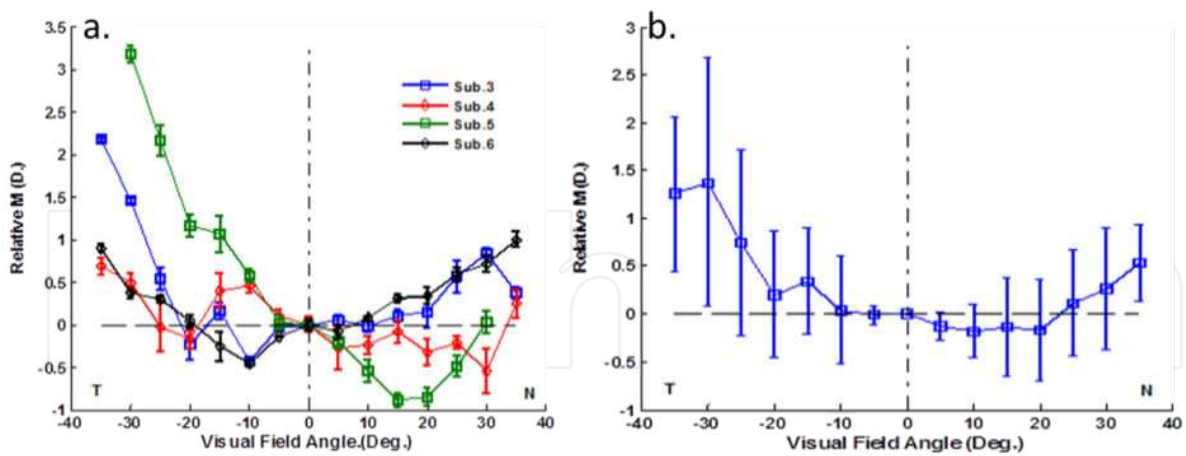
Figure 8. a) Relative M as a function of visual field angle for the naked eye of 4 myopic subjects separately. Error bar indicate the within-subject variance of 5 repeated measurements. b) Relative M as a function of retina eccentricity for myopes. Error bar indicate the standard deviation of the four myopic subjects.
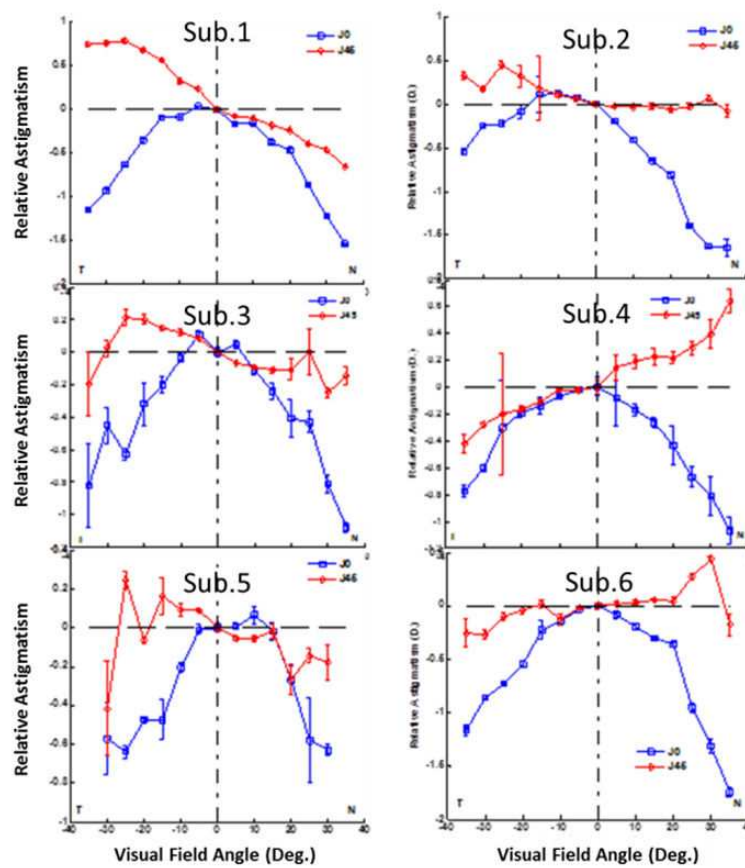

Figure 9. a) Relative J_0 and J_{45} as a function of visual field angle for the six naked eye. Symbols show the mean and error bar indicate the standard deviation of 5 repeated measurements. b) Mean value of the relative J_0 and J_{45} of the six subjects. Error bar indicate the standard deviation of these six subjects.

In another published study, the mean data show a monotonic increase in PRM with eccentricity that is approximately linear with a slope of 0.01 diopters/deg of eccentricity. Thus for an eccentricity of E degrees, PRM is approximately E percent of foveal refractive error in the naked eye. [110]

6.2. Effect of contact lenses on field curvature and peripheral astigmatism

In the group with 4 myopic subjects, the mean value of the change of mean spherical and astigmatism across the horizontal visual field without any correction and with full SCLs correction were shown in Fig. 10 and Fig. 11. With the SCLs corrections, which rendered the fovea conjugate to infinity, the M component still showed a relatively hyperopic shift to the peripheral visual field away from the center. In most of the measurement positions, spherical equivalent had larger hyperopic value after subjects wearing SCLs than their naked eye's data. This suggested that using Acuvue 2 SCLs in this experiment to fully correct the foveal refractive error might cause more hyperopic shift in the peripheral visual field. The nasal-temporal asymmetry after wearing the SCL was not apparent anymore (Fig.10). This result suggested that either corneal shape was responsible for the asymmetry or it was an artifact of CL movement. In the new experiment, the measurements will be taken by rotate subject's head instead of eye rotation. This can eliminate the artifact of SCLs movement and will give us answer about this issue. J_0 was the major contributor for the increase of astigmatism in large visual angle. After full correction with SCLs, J_{45} did not change much across the horizontal visual field, but greater J_0 (more negative) was found in the experiment (especially across the temporal retina) (Fig.11). However, large between-subject differences were found. Only 4 subjects who had very different center refractive error participated in the study. Hopefully, the variance will be reduced by recruiting more subjects who have similar central refractive status in the future study.
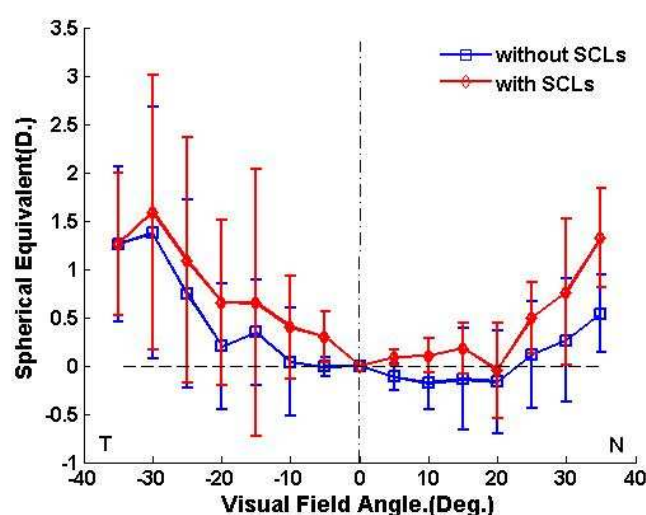

Figure 10. The effect of SCLs on relative M as a function of visual field angle with and without SCLs correction. Error bar indicate the standard deviation.
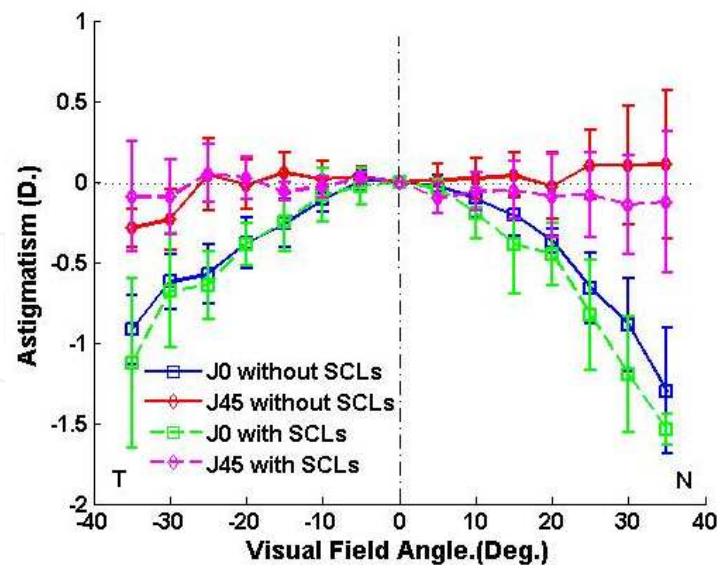
Figure 11. The effect of SCLs on relative J_0 and J_{45} across the horizontal visual field with and without SCLs. Red lines are J_{45}, blue lines are J_0. Dash lines indicate the astigmatisms after subjects wear the SCLs. Error bar shows the standard deviation.

Compared to the naked eye, curvature of field was reduced, and in some cases reversed in sign, by contact lenses.

6.3. Contact lens effect on total sphero-cylindrical blur

The results described above show that defocus (M) and astigmatism (J_0) both vary across the visual field. If image quality is a driving force for myopia progression as suggested previously, [78-82] then it is important to determine the combined effects of M and J_0. The effect of contact lenses may be complex because, as shown above, relative hyperopic defocus is reduced by contact lenses, but peripheral astigmatism increases. Therefore, to determine the effect of contact lenses on peripheral image quality, we need to quantify and compare the total sphero-cylindrical image blur on the peripheral retina before and after wearing contact lenses.

In one of our published studies, [110] the average image blur caused by sphere and cylinder in naked eye increased to 2 D at 35° periphery relative to the eye's optical axis. SCLs did not have a consistent effect on sphero-cylindrical blur but RGP lenses consistently reduced the blur across the visual field ($p < 0.01$, non-parametric sign test) by approximately 0.25 diopter.

7. Peripheral image quality and contact lens correction

7.1. Variation of higher-order aberrations with visual field eccentricity

The data was also analyzed in Zernike coefficient terms in order to study the change of high-order aberrations as a function of the visual field angle. Coefficients from 2nd-to 6th-order were used to describe the wavefront aberrations. The change of mean (all 6 subjects) relative 2nd-

order aberration as a function of visual field angle was shown in Fig.12. The 2nd-order aberration increased with the visual field angle. Across the horizontal visual field, C_2^2 was the major contributor for the change of 2nd-order aberration (Fig.13 b). Since positive value of C_2^2 indicates Against-The-Rule (ATR) astigmatism and negative value of C_2^2 indicates With-The-Rule (WTR) astigmatism, mean value of C_2^2 in this experiment suggested that the astigmatism changed from WTR to ATR with the increasing of visual field angle from center to periphery (Fig.13 a). Considerable differences occurred among the 6 subjects. This might partly due to the different center refractive error of these six subjects had effects on the peripheral refraction shift.
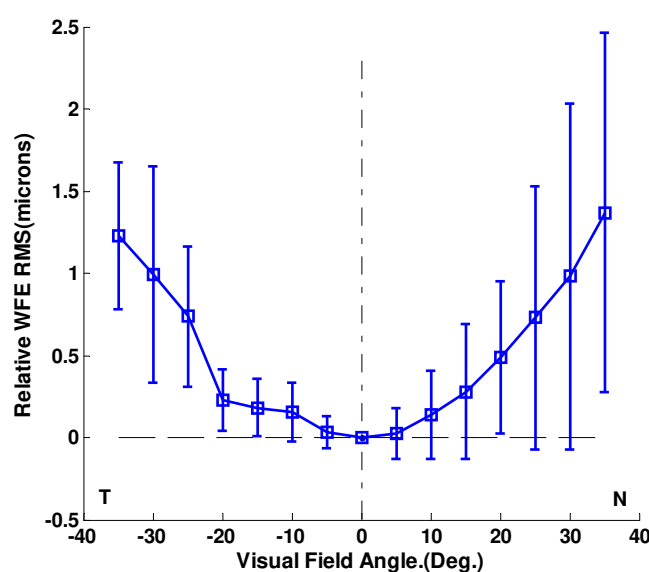

Figure 12. Relative RMS in 2nd-order aberration across the horizontal visual field of the naked eye. Error bar indicate the standard deviation among the six subjects.
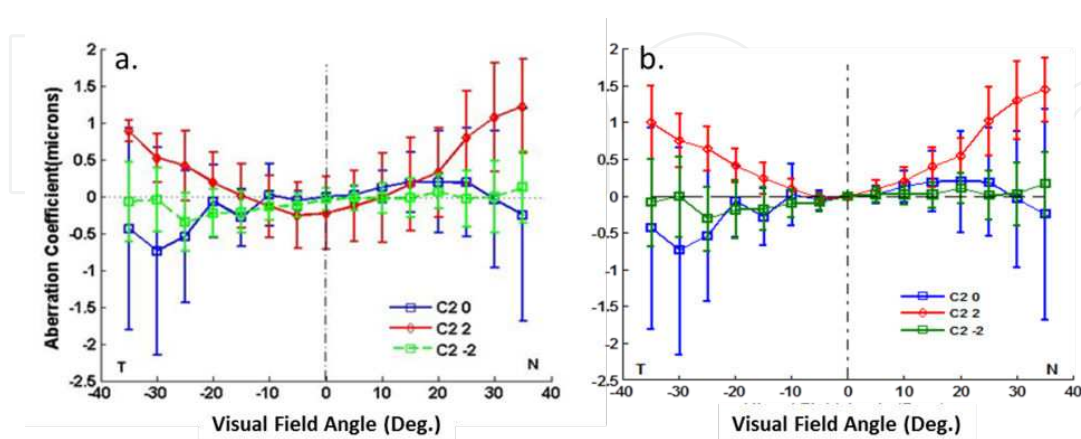

Figure 13. a) The change of Zernike coefficients in the 2nd-order aberration without any correction with the increasing of visual field angle. The data is the mean value of six subjects. Error bar indicate the standard deviation. b) Relative Zernike coefficients in 2nd-order aberration as a function of visual field angle. Error bar indicate the standard deviation.
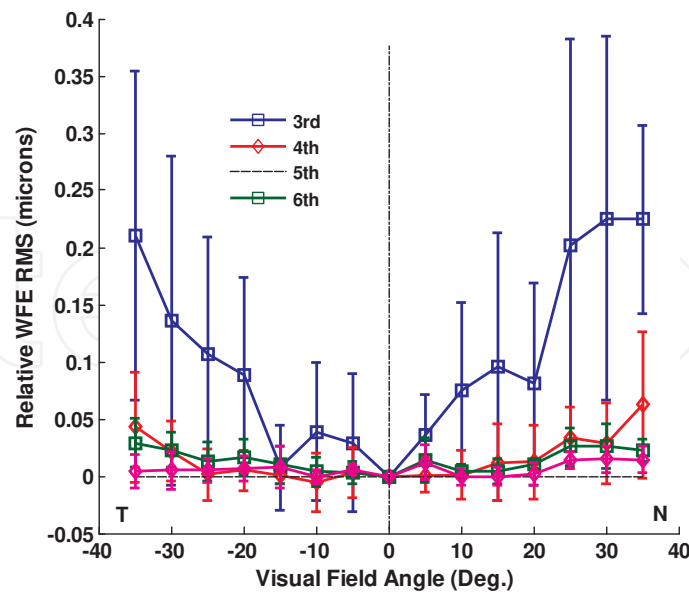
Figure 14. Relative RMS value of high order aberrations' change across the horizontal visual field without any correction for the all six subjects. Error bar indicate the standard deviation.

The high order aberrations (3rd-to-6th-, in this experiment) basically showed the same pattern with Atchison & Navarro's data [62, 111]. The 3rd-, 4th-and 5th-order aberrations showed an increasing magnitude with the visual field angle. Changes of 6th-order aberration were quite small across the horizontal visual field. The nasal-temporal asymmetry of 3rd-order aberration was not as apparent as Atchison's data. In the nasal visual field, there was a factor of 2.8 increasing in 3rd-order aberration. Which reported by Atchison was 5 and by Navarro was 2.5. For temporal visual field, there was a factor of 2.6 for 3rd-order aberration, which reported by Atchison was 3. For 4th-and 5th-order aberrations, a small increase of magnitude with the increasing visual field angle was also noticed. Big individual variance was found in our data as well as in Atchison and Navarro's data (Fig. 14). The sample size was small both in this experiment and previous studies.

Horizontal coma (C_3^1) was a major contributor to the increase of 3rd-order aberration in the peripheral visual field and it showed a linear dependence on the visual field position. This contrasted with changes of vertical coma (C_3^{-1}) and trefoils (C_3^3 and C_3^{-3}), which were quite flat across the visual field. This linear relationship between horizontal coma and retina eccentricity was predicted by Seidel theory [112], and both Atchison's data and my data showed this relationship in the human eye (Fig.15). Although there were large individual variances, both spherical aberrations (C_4^0) and secondary astigmatism (C_4^2) showed a quadratic dependence on visual field position. This relationship between C_4^0, C_4^2 and visual field position was also predicted by Seidel Theory. The spherical aberration (C_4^0) showed a positive value in the fovea (most people have positive spherical aberration in the un-accommodated state for foveal vision [28]). However, the magnitude of spherical aberration reduced into the horizontal periphery and finally became negative (Fig. 16).
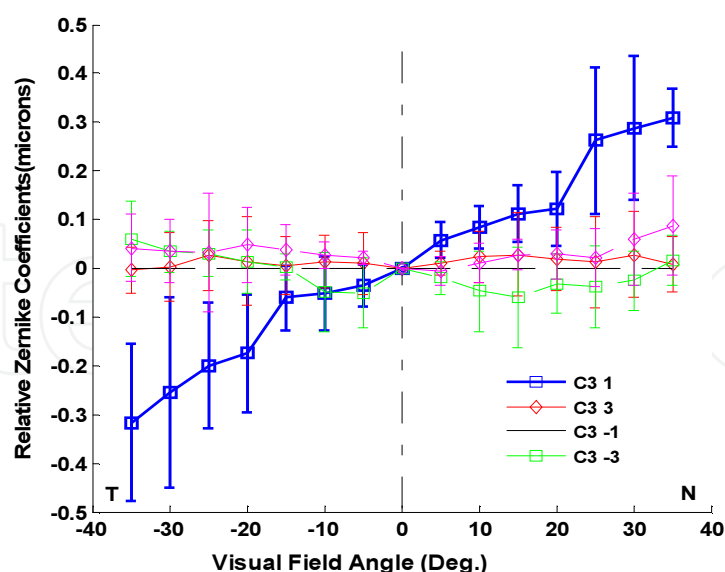
Figure 15. Relative Zernike coefficients in 3rd-order aberration across the horizontal visual field without any correction. Data is mean value of 6 subjects. The blue line is the horizontal coma ($C_3{}^1$). Error bar indicate the standard deviation.
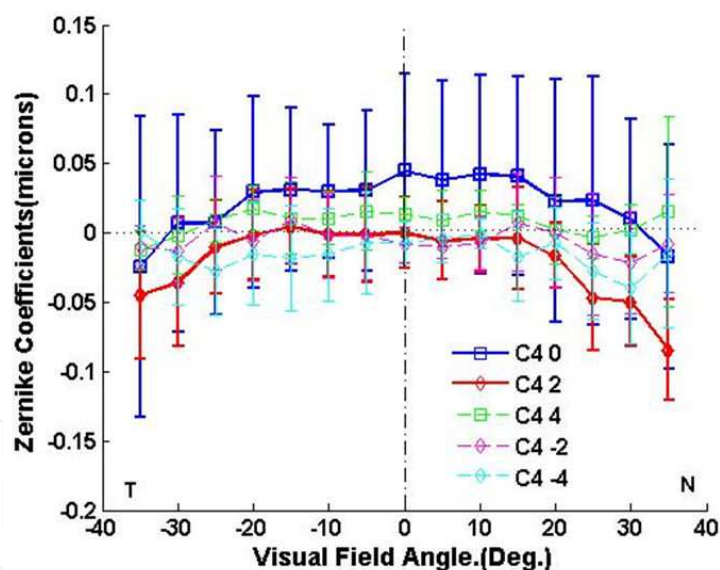

Figure 16. a) The change of Zernike coefficients in 4th-order aberration across the horizontal visual field without any correction. Blue line and red line are spherical aberration ($C_4{}^0$) and secondary astigmatism ($C_4{}^2$), respectively. Data is mean value of 6 subjects. Error bar indicate the standard deviation. (From the figure, we can notice the $C_4{}^0$ is positive value in the fovea and finally become negative in the far periphery) b) Relative Zernike coefficients in the 4th-order aberration. Error bars was omitted in order only to show the change pattern of $C_4{}^0$ and $C_4{}^2$ more clearly.

After wearing SCLs, the changes of 2nd-to 6th-order aberrations kept the similar pattern from center to periphery as those uncorrected eyes. Large individual variances still existed, and the 2nd-to 5th-order aberration increased with the visual field angle. The nasal-temporal asymmetry was not apparent as well. In the 3rd-order aberration, after wearing soft contact lens, the

horizontal coma still somehow showed a linear dependence with the horizontal visual angle. The spherical aberration and secondary astigmatism continued to show quadratic dependences on the visual field positions after soft contact lenses wearing. (Fig. 17 a, b, c & d)
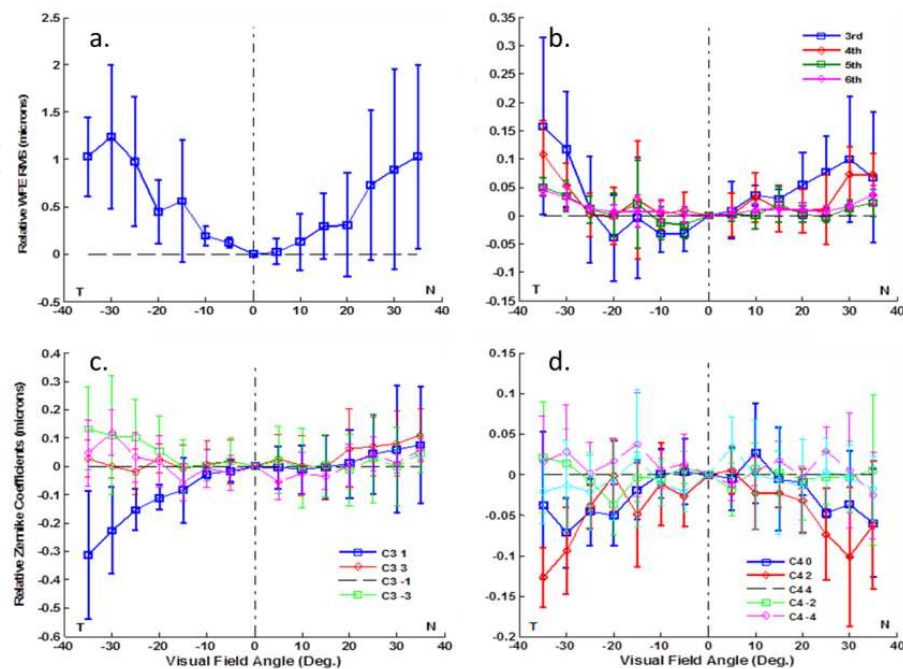

Figure 17. The relative value of 2nd-to 6th-order aberrations and Zernike coefficients across the horizontal visual field with SCLs fully corrected the subjects' foveal vision. Error bar indicate the standard deviation of the 4 SCL wearer subjects. a). Mean relative value of 2nd-order aberration. b). Mean relative value of 3rd-to 4th-order aberrations. c). Relative Zernike coefficients in the 3rd-order aberration. d). Relative Zernike coefficients in the 4th-order aberration.

7.2. Effect of contact lens correction on ocular higher-order aberrations

After wearing SCLs to fully correct the foveal refractive error, 2nd-order aberration increased in the most positions in temporal visual field but decreased in most positions in nasal visual field (Fig. 18 a & b). This was consistent with the data shown in Fig.7 & 8.
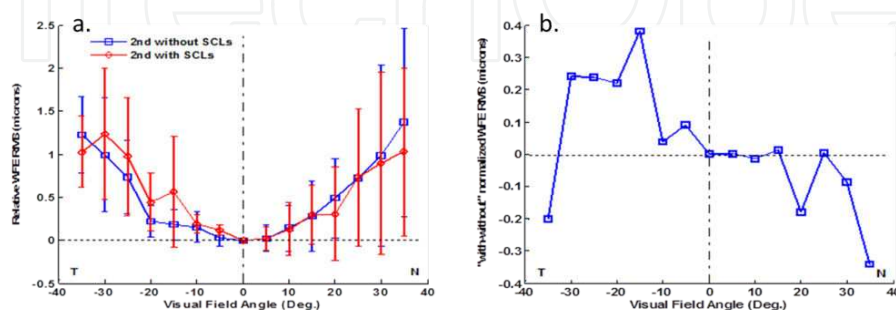

Figure 18. a) The change of 2nd-order aberrations across the horizontal visual field with and without SCL correction. Error bar indicate the standard deviation. b) By subtracting the naked eye's data, the curves in the figure indicate the effect of SCLs on relative wavefront RMS of the subjects. Negative value means the RMS becomes smaller after wearing SCL.

When comparing 3rd-to 6th-order aberrations before and after wearing soft contact lenses, we found that the magnitude increasing rate of 3rd-order aberration decreased after SCLs correction compared to that in the naked eyes, especially beyond 20 degree nasal visual field (Fig. 19 a & b). A 1.4 fold increase in 3rd-order aberration of the nasal visual field after wearing soft contact lenses compared to the 2.5 fold before wearing the soft contact lenses was found. Since the irregular corneal anterior surface contributed significantly to the asymmetric aberrations, the eye with soft contact lenses more or less smoothed the anterior corneal surface, thus the reduction of 3rd-order aberration after contact lens fitting was anticipated. Another more possible reason might be the movement of SCLs in the eye. When the eye turned around to the far periphery to fixate on the target, SCLs would move in the opposite direction, thus the measurements taken by aberrometer in these visual angles would not be the exact reading taken if the SCLs could move with the eyes perfectly but this might be a great advantage of SCLs in real life. RGP lens can probably reduce 3rd-order aberration more since RGP lenses have larger movement than SCLs (if the measurements are still taken in the same way with the eye rotation to fixate on target in different visual angle). After wearing SCLs, the 4th-order aberration increased to the far horizontal periphery beyond center 50 degrees. This, again, might be caused by the movement of the contact lenses. The 5th-and 6th-order aberrations also slightly increased after wearing soft contact lenses in the temporal visual field (Fig. 19 a & b).
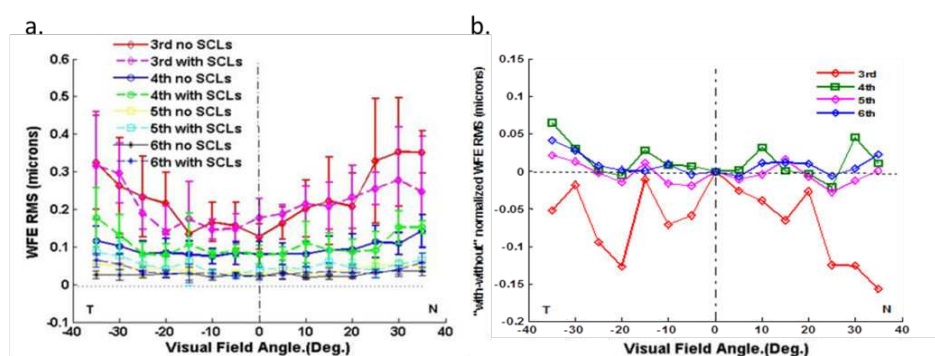

Figure 19. a) The change of 3rd-to 6th-order aberrations across the horizontal visual field with and without SCLs correction. Error bar indicate the standard deviation. b) Data after wearing SCLs subtract naked eye's data. Negative value means after wearing SCLs, the RMS wavefront error become smaller.

Only horizontal coma was shown in Fig. 20a), because the other coefficients were quite small across the horizontal visual field comparing to horizontal coma in both before and after SCLs fitting. After wearing SCLs, the slope of that linear relationship between the C_3^1 and visual field angle became flatter (Fig.20 a). This contributed to the overall decrease of 3rd-order aberration after wearing SCLs. For the 4th-order aberration, since the spherical aberration (C_4^0) and secondary astigmatism (C_4^2) were the two major components which contributed to the 4th-order aberration change across the horizontal visual field, data were plotted of these two coefficients only with and without SCLs correction (Fig.20 b & c). The spherical aberration (C_4^0) did not show significant differences across all the retina eccentricity before and after contact lenses fitting. However, secondary astigmatism (C_4^2) showed larger magnitudes to the horizontal periphery compared to the uncorrected eye (Fig.20 b & c). This might help to explain

the increase in the magnitude of 4th-order aberration in the far periphery. Both the primary astigmatism and secondary astigmatism became larger in the large off-axis visual angle after wearing SCLs, but there was no adequate explanation currently to explain this.
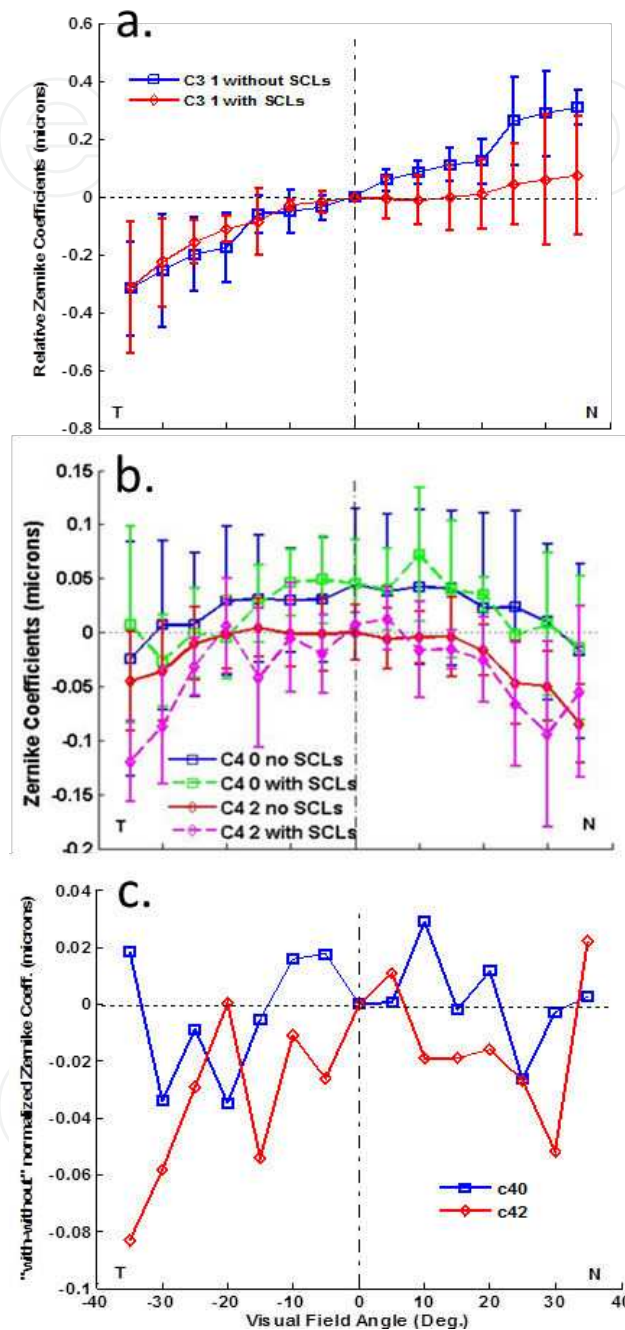

Figure 20. The change of Zernike coefficients as a function of visual field angle. The data are the mean value got from 4 myopic subjects with and without SCL correction. Error bar indicate the standard deviation. a). Change of the relative horizontal coma (C_3^1) across the horizontal visual field before and after SCLs correction. b). Change of spherical aberration (C_4^0) and secondary astigmatism (C_4^2) across the horizontal visual field before (solid lines) and after (dash lines) SCLs correction. c). Data after wearing SCLs subtract naked eye's data. Negative value means Zernike coefficients of C_4^2 became larger after wearing SCLs comparing to naked eyes.

7.3. Peripheral image quality with and without contact lens correction

Image quality was assessed with the VSOTF metric [113, 114] for the complete wavefront aberration (including 2nd order aberrations) measured over the full entrance pupil of each eye in another published study Without contact lens correction, VSOTF gradually decreases from center to periphery. With contact lens correction, image quality improves greatly both in the center and in the periphery. This improvement is due mainly to a reduction in 2nd order aberrations. RGP lens correction shows a trend of better image quality than SCLs across the whole visual field. Image quality drops quickly from center to the periphery after contact lens correction.

8. Conclusion

Both SCL and RGP lenses reduce the degree of hyperopic field curvature present in myopic eyes, but only RGPs reduce the relative amount of image blur on the peripheral retina. Although our study was motivated by the myopia question, the results pertain also to the perceptual quality of peripheral vision. The visual benefit of improved image contrast for peripheral vision obtained by RGP lenses should outweigh the visual benefit of SCLs. The tradeoff between reduced field curvature but increased peripheral astigmatism with RGP correction limits the net improvement of image blur on the peripheral retina that might, in turn, limit RGP lens effectiveness for improving vision or controlling myopia progression. Our results suggest that axial growth mechanisms that depend on retinal image quality will be affected more by RGP than by SCL lenses. These results provide some guidance for future designs of contact lenses to control myopia progression.

Contact lens increases higher-order aberrations in the peripheral visual field except 3rd-order Zernike terms. RGP lenses 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 IQ. If the eye has good IQ initially, changes in HOA have a relatively large effect on IQ. But if the eye has poor IQ initially, HOA will have relatively small effect on IQ. 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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