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Optical Modeling and Analysis of Peripheral Optics of Contact Lenses

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ABSTRACT

Background: Degraded peripheral vision has been hypothesized to be a stimulus for the development of foveal refractive error. Contact lenses have been widely used to correct central vision, but their impacts on peripheral vision are still unknown. The purpose of this study was to use optical model software to evaluate the peripheral optics of rigid gas permeable (RGP) and soft contact lenses (SCLs) in isolation. This will better assist us in understanding their peripheral optical performances on human eyes. **Methods**: An optical design software package (Zemax EE) was used to model peripheral optics of Menicon RGP lens and Acuvue 2 SCLs. Profiles of sphero-cylindrical power and major higher-order aberrations were computed in 10˚ steps out to 40˚ off-axis eccentricity for –3.0 D central focal power contact lens. The results of optical modeling were analyzed and compared with previously published experimental data. **Results**: –3.0 D RGP lenses and SCLs had –1.4 D and –2.0 D dioptric power at 40˚ eccentricity, respectively. The reduced dioptric power in the periphery of the analyzed contact lenses quantitatively matched with the reduced amount of hyperopic field curvature found from experimental data when these contact lenses fitted on human eyes. Cylindrical power increased to 0.3 D ~ 0.4 D at 40˚ eccentricity for both lens types. In addition, both contact lens types produced higher order aberrations, namely 1.2 µm coma and 0.15 µm spherical aberration at 40˚ eccentricity. **Conclusions**: Compared to SCLs, RGP lenses with equal focal power had less dioptric power in the periphery. Both RGP lenses and SCLs produced the same amount of major higher-order aberrations with increasing of the field angle. Some of these results can be used to predict and understand the peripheral optical performance of contact lenses on human eyes.

Keywords: Contact Lens; Peripheral Optics; Aberrations; Optical Model

1. Introduction

Degraded peripheral vision has been hypothesized to be a stimulus for the development of foveal refractive error. [1-4]. Based on the “grow to compensate hyperopic defocus” [1-3] or the “grow to clarity” [4] hypothesis and local retinal mechanisms [5-8], eyes of individuals even with perfect central vision, but with peripheral hyperopic refractive error or blurred peripheral image, might still develop myopia.

Contact lenses (CLs) are widely used treatments for correcting foveal defocus and astigmatism. With fully corrected foveal vision achieved, peripheral refractive error and aberrations with contact lens correction are still largely unknown. Some recent studies have shown the effects of CLs on peripheral refraction and image quality [9-11]. Results from those studies indicated that, after CLs correction, peripheral refraction will be influenced by the contact lens design and materials when a contact lens is prescribed to correct on-axis refractive error. Our previous study [9] compared peripheral refraction with correction of Rigid Gas Permeable (RGP) lenses and Soft Contact Lenses (SCLs) and suggested that both lens types reduced the degree of hyperopic field curvature present in the periphery of myopic eyes, with RGP lenses having a greater effect. Moreover, our results have shown that RGP lenses introduced more oblique astigmatism than SCLs, which as a tradeoff, limited the possible effect of RGP lenses on myopia progression control.

The above studies were based on experimental measurements of the peripheral optics of the human eye with and without CLs. The experimental methods are time consuming and labor intensive since investigators need to repeat the measurements along horizontal or vertical meridians in 5˚ or 10˚ steps out to 40˚ off-axis eccentricity using different instruments [2,12-19]. Although new techniques have been developed to facilitate easy and fast measurements of human eyes’ peripheral optics, [20, 21] it is still a major methodological obstacle for researchers who are interested in studying peripheral vision.

Optical modeling results of off-axis optical characteristics of human eyes with CLs correction have also been previously reported [22,23]. However, there are few studies focused on characterizing peripheral optics of CLs in isolation. We anticipate that the different types of CLs with varying design characteristics and materials have a major impact on the differences in peripheral image quality. To characterize the off-axis optics of different CLs, we can either experimentally measure their peripheral refraction and aberrations in isolation or use optical design software for modeling off-axis optical characteristics of those CLs. Percy *et al.* [10] used a “Power Mapper” system, which scans a narrow laser beam parallel to the optical axis across the entire lens surface, to measure power profiles across the optic zone (OZ) of the CLs. However, this method did not measure the actual off-axis power of the contact lens which needs pencils of light coming from varying off-axis field angles. A physical human model eye has been developed recently and provided the ability to assess the optical performance of CLs in varying off-axis positions [24]. In this study we use the popular optical design software Zemax to evaluate the peripheral optics of different contact lenses, SCLs and RGP lenses, in isolation. This will better assist us in understanding their peripheral optical performances when fitted on human eyes.

2. Methods

An optical design software package (Zemax EE, Zemax Corporation, San Diego, Feb. 2010 version) was used to run a ray-tracing program to model the peripheral optics of Menicon XT RGP lenses (Z material, Menicon Co. Ltd.) and Acuvue 2 SCLs (Vistakon Division, J & J Vision Care, Inc.). The parameters of the different lens designs were obtained from the manufacturers. In the following text the abbreviations RGP lenses refers to Menicon Z XT contact lenses and SCLs refers to Acuvue 2 contact lenses.

A Zernike aberrations table was generated and extracted from the Zemax modeling results. The sphero-cylindrical power components were converted from the Zernike coefficients using the following equations.

$$\begin{aligned} M &= \frac{-4\sqrt{3}}{r^2}C_2^0 \\ J_0 &= \frac{-2\sqrt{6}}{r^2}C_2^2 \\ J_{45} &= \frac{-2\sqrt{6}}{r^2}C_2^{-2} \end{aligned} \quad (1)$$

where M represents the spherical equivalent, J_0 represents with-the-rule (WTR) astigmatism and against-the-rule astigmatism (ATR), J_{45} represents oblique astigmatism with axes at 45 degrees and 135 degrees. C_2^0, C_2^2, C_2^{-2} are Zernike coefficients for defocus, WTR or ATR astigmatism and oblique astigmatism terms, respectively. In these equations, r is the pupil radius, or aperture radius.

Based on the contact lenses parameters as provided by the manufacturers, profiles of sphero-cylindrical power and major higher-order aberrations (up to the 4th Zernike order) were computed in 10˚ steps out to 40˚ off-axis eccentricity for –3.0 D RGP lenses and –3.0 D SCLs. All computations were done for an aperture size of 6 mm. Peripheral profiles of field curvature, astigmatism, coma and spherical aberration of CLs with varying central dioptric power from –1.0 D to –6.0 D in 1.0 D steps have also been modeled. The results of optical modeling were analyzed and compared with previously published experimental data [9,25].

3. Results

Both types of contact lenses produced less negative power for off-axis incident pencils of light than for on-axis pencils of light. **Figure 1** is a comparison of the mean spherical equivalent (M) across the lens up to 40 degrees of off-axis angle in the two types of contact lenses, both having a central focal power of –3.0 D.

As shown in **Figure 1**, at a 40 degrees off-axis field angle the dioptric power of the RGP lens decreased to –1.4 D and the dioptric power of the SCL decreased to –2.0 D.

Contact lenses, just like other optical elements, produce more cylindrical power with increasing off-axis angle. As depicted in **Figure 2**, both the RGP lens and SCL introduce ATR astigmatism in off-axis eccentricities. However the RGP lens has a stronger effect. At 40˚

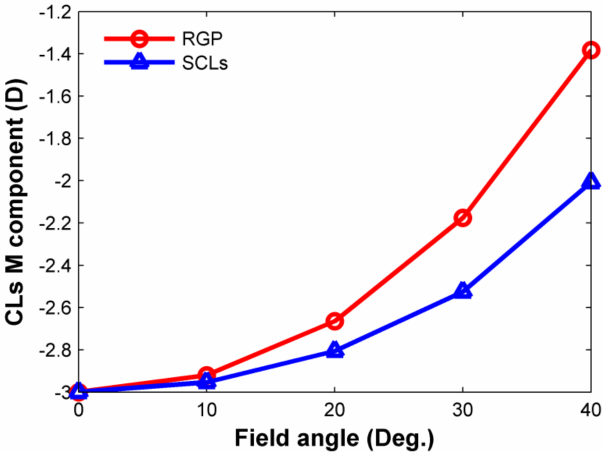

Figure 1. Refractive power variation in relation to the field angle for different contact lenses modeled by Zemax software. The contact lenses used in this simulation had -3.0 D central focal power. The power profile of the RGP lens is represented by the red curve and the power profile of the SCL is represented by the blue curve.

eccentricity, –3.0 D the RGP lens and the SCL produce –0.38 D and –0.32 D astigmatism, respectively. Compared to the changes in the spherical power profiles the increases in off-axis astigmatism are small.

The experimental results showed that the effect of contact lenses on the peripheral curvature of field was depended on the CLs central dioptric power. The higher the corrective power of the lens, the more effect it had on the changes of peripheral curvature of field. The optical modeling of contact lenses in isolation also supports these empirical data (**Figure 3**). Both contact lenses showed increased positive focal power values of Peripheral Relative M (PRM) when the central dioptric power varied from –1.0 D to –6.0 D. The amounts of J_0 introduced by both types of CLs also increased systematically in the periphery with increased lens power. Comparing J_0 profiles of RGP lenses with SCLs, RGP lenses introduced more cylindrical power in the periphery than did SCLs.

Simulation of Major Higher-Order Aberrations

The optical modeling of major higher-order aberration coefficients indicated that RGP lenses and SCLs with same central power introduced the same amount of coma in the off-axis field angle. Both RGP lenses and SCLs produced negative spherical aberration (SA) which became more negative toward the contact lenses peripheries (**Figure 4**).

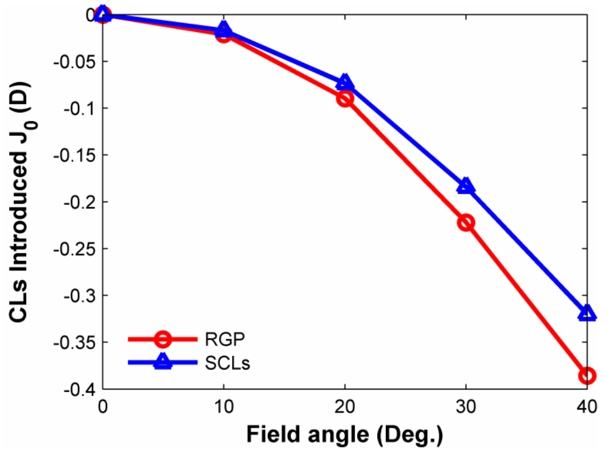

Figure 2. Cylindrical power variation in relation to the field angle for different contact lenses modeled by Zemax software. The contact lenses used in this simulation had -3.0 D central focal power. The power profile of the RGP lens is represented by the red curve and the power profile of the SCL is represented by the blue curve.

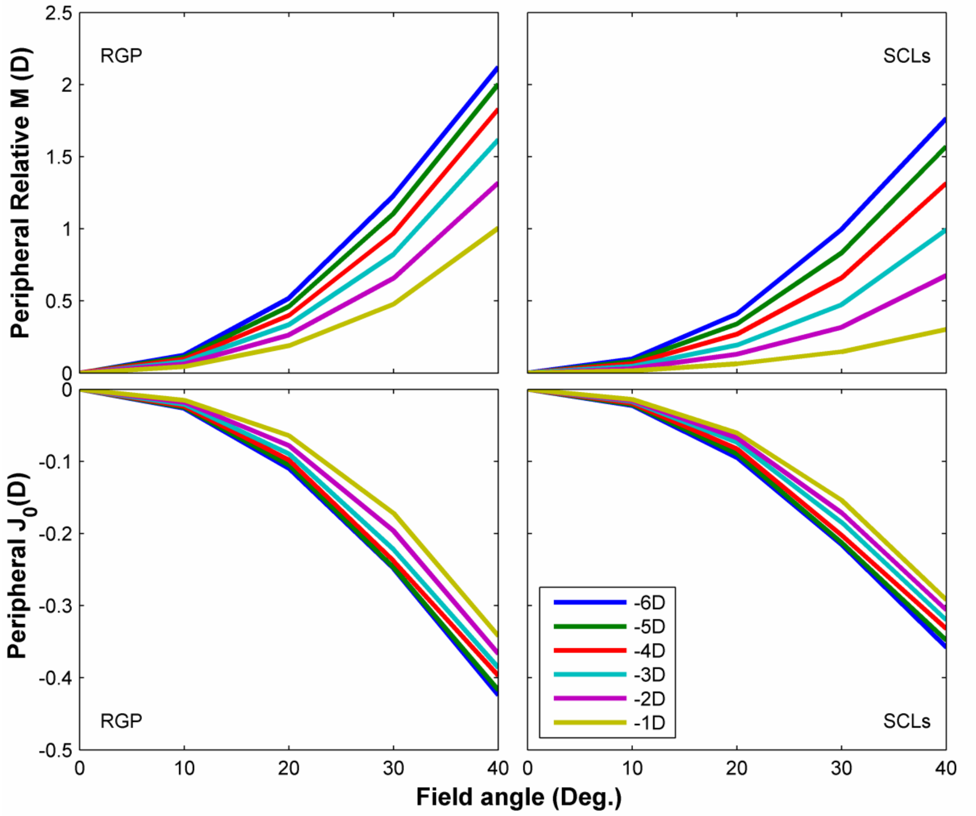

Figure 3. Contact lens power profiles varied depending on the contact lenses central focal power. The upper two panels show the profiles of peripheral relative defocus (*M*) and the lower two panels show the profiles of peripheral WTR and ATR astigmatism (J_0).

The amount of off-axis coma and spherical aberration increased with dioptric lens power for both RGP lenses and SCLs (**Figure 4**). However it has to be noted that the Zemax modeling of higher-order aberrations induced by the contact lenses were done in isolation. Therefore the results of these simulations may differ from experimental findings when the lenses interact with the optical components of the patients' corneas.

4. Discussion

One purpose of the current study was to investigate how efficient the optical characteristics of contact lenses can be transferred to the eye when fitting CLs. The results presented in this study indicate that the optical properties of CLs in isolation change at various field angles. The comparison of these results with previous experimental data allows a better understanding and prediction of the peripheral optical profiles for different types of contact lenses when fitted in the eyes. **Table 1** allows a comparison of experimental findings for a –3.0 D myopic eye with optical modeling results for a –3.0 D RGP lens and a –3.0 D SCL respectively.

For field angles ranging from 5 degrees up to 25 degrees, both the RGP lens and the SCL induced a relative myopic defocus. Whereas the SCL demonstrated this throughout the entire peripheral field up to 35 degrees, the RGP induced a relative hyperopic defocus for 30 degrees and 35 degrees field angles (**Table 1**).

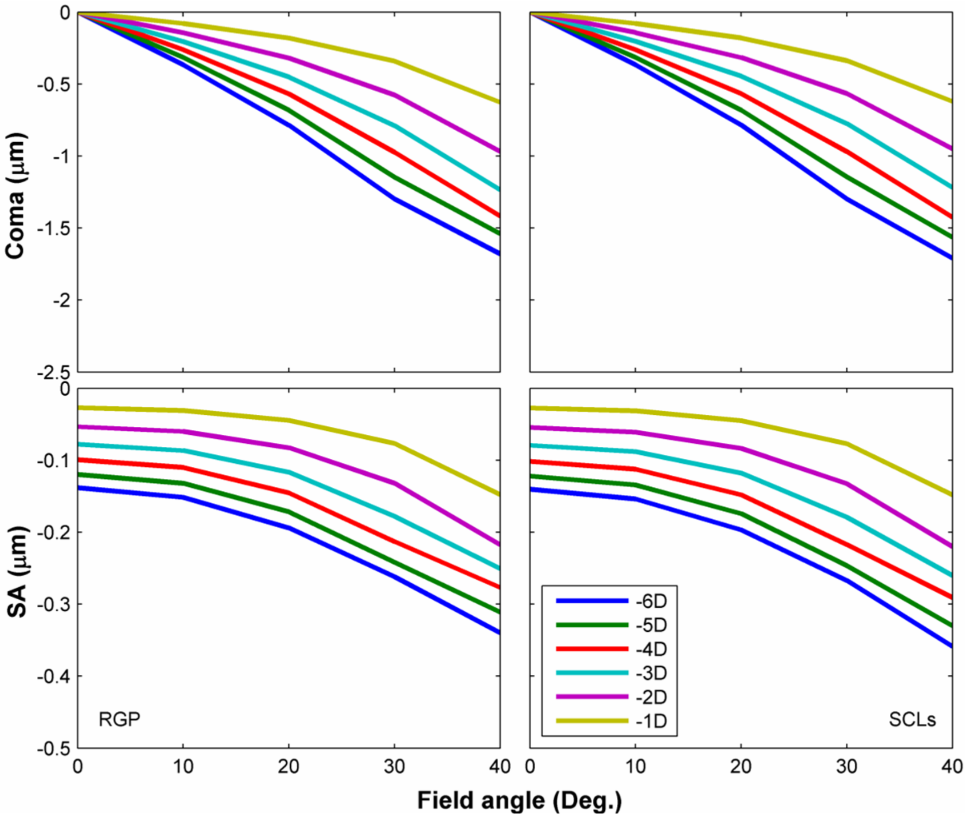

Figure 4. Coma and spherical aberration (SA) varied with field angle in different contact lenses. The focal power values of the contact lenses used in this Zemax modeling varied from -1.0 D to -6.0 D. The upper two panels show the profiles of coma and the lower two panels show the profiles of spherical aberration (SA).

Table 1. A comparison of optical modeling data for contact lenses from this study and experimental data for an uncorrected myopic eye, adapted from a previous study [9].

Data values (diopter)	**Field angle** (degree)							
	0	5	10	15	20	25	30	35
Experimental (uncorrected eye)	–3.00	–2.89	–2.77	–2.70	–2.59	–2.41	–2.29	–2.03
RGP modeling	–3.00	–2.97	–2.92	–2.80	–2.66	–2.45	–2.18	–1.80
SCL modeling	–3.00	–2.98	–2.95	–2.91	–2.81	–2.69	–2.53	–2.27

The decreased lens power in the peripheral field can help to explain why SCLs partially correct PRM while RGP lenses over-correct RPM at large field angles (25˚ and 30˚). In the companion paper, one of the major statements is "for an eccentricity of E degrees, PRM is approximately E percent of foveal refractive error in the naked eye" [9]. For example, when measuring at 35˚ eccentricity, a –3.0 D myopic eye has about 35% × 3.0 D = 1.05 D less refractive myopic error relative to its center, which equals a remaining amount of –1.95 D myopia at 35˚ visual field angle. A RGP lens with –3.0 D central focal power has a peripheral focal power of –1.8 D at 35 degrees field angle, which will under-correct the eye's refractive error at this eccentricity and result in a myopic field curvature. On the contrary, a –3.0 D SCL has a spherical power of –2.27 D at 35 degrees which will over-correct the eye's refractive error resulting in a hyperopic field curvature (**Figure 5**).

The above analysis indicated that differences of peripheral power profiles in SCLs and RGP lenses can help to explain the experimental observations of changes in PRM when these lenses were used to correct central refractive errors. With contact lens correction the total optical system of the eye consists of the contact lens, the tearfilm, the cornea and the crystalline lens. We analyzed the data of curvature of field profiles for the –3.0 D myopic uncorrected eye as well as the –3.0 D contact lenses listed in **Table 1**. By ignoring the influence of the tear film when wearing a contact lens the blue and red curves in **Figure 6** represent the normalized PRM, PRM value as a fraction of center M, of a SCL and a RGP lens, respectively. A comparison of data from the optical modeling and experimental findings shows that these data have a close match for visual field angles up to 25 degrees.

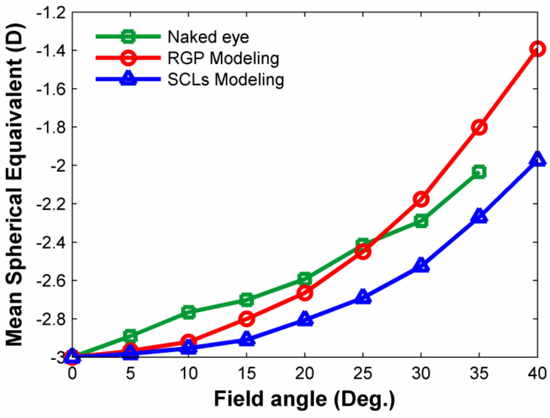

Figure 5. Comparison of experimental data of a –3.0 D myopic eye's curvature of field profile with optical modeling data of –3.0 D contact lens power profiles for varying field angles. The green curve represents the experimental data adapted from a previous paper. The red and blue curves represent the optical modeling results for a RGP lenses and a SCL, respectively.

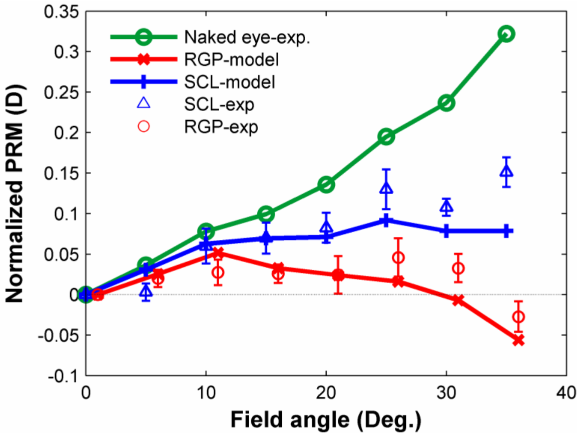

Figure 6. Normalized PRM as a function of varying field angles. The green curve represents experimental data in uncorrected eyes. The blue and red curves indicate normalized PRM by subtracting uncorrected experimental data of SCLs and RGP lenses from modeling data, respectively. The blue triangle and the red circle symbols represent experimental data for the SCLs and the RGP lenses, respectively. The error bars indicate the standard error of the mean.

This suggests that the dioptric power of the contact lenses can be effectively transferred to the eye from the center to the mid periphery. When wearing contact lenses the tear film plays a minor role in the formation of peripheral defocus.

Optical modeling data for astigmatism (J_0) and other major higher-order aberrations (Coma and SA) of the RGP lenses and SCLs did not generate comparable results with the experimental data [9,25]. This might be due to the conformity of the contact lenses with the front corneal surface which was not taken into account in the Zemax modeling.

In conclusion, RGP lenses with equal focal power had less dioptric power in their periphery compared to SCLs. Both RGP lenses and SCLs produced the same amount of major higher-order aberrations with the increase of the field angle. Optical modeling of peripheral optics of CLs in isolation can be a good predictor for changes in PRM up to a field angle of 25 degrees. Within this range the modeling matched appropriately with previously observed experimental findings.

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