Changes in Peripheral Refraction, Higher-Order Aberrations, and Accommodative Lag With a Radial Refractive Gradient Contact Lens in Young Myopes

Jaume Pauné, M.Sc.*, Solène Thivent,* M.Sc.*, Jesús Armengol,* Ph.D.*, Lluisa Quevedo,* Ph.D.*,*
Miguel Faria-Ribeiro, M.Sc.*, and José M. González-Méijome,* Ph.D.

Purpose: To evaluate changes in the peripheral refraction (PR), visual quality, and accommodative lag with a novel soft radial refractive gradient (SRRG) experimental contact lens that produces peripheral myopic defocus.

Methods: 59 myopic right eyes were fitted with the lens. The PR was measured up to 30° in the nasal and temporal horizontal visual fields and compared with values obtained without the lens. The accommodative lag was measured monocularly using the distance-induced condition method at 40 cm, and the higher-order aberrations (HOAs) of the entire eye were obtained for 3- and 5-mm pupils by aberrometry. Visual performance was assessed through contrast sensitivity function (CSF).

Results: With the lens, the relative PR became significantly less hyperopic from 30° to 15° temporally and 30° nasally in the M and J0 refractive components ($P<0.05$). Cylinder foci showed significant myopization from 30° to 15° temporally and 30° to 25° nasally ($P<0.05$). The HOAs increased significantly, the CSF decreased slightly but reached statistical significance for 6 and 12 cycles per degree ($P<0.05$), and the accommodative lag decreased significantly with the SRRG lens ($P=0.0001$). There was a moderate correlation between HOAs and CSF at medium and high spatial frequencies.

Conclusion: The SRRG lens induced a significant change in PR, particularly in the temporal retina. Tangential and sagittal foci changed significantly in the peripheral nasal and temporal retina. The decreased accommodative lag and increased HOAs particularly in coma-like aberration may positively affect myopia control. A longitudinal study is needed to confirm this potential.

Key Words: Peripheral refraction—Aberrometry—Lag of accommodation—Radial refractive gradient contact lens—Myopia.

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Myopia should no longer be considered simply as a refractive error.[1] Myopic eyes are prone to several ocular pathologies such as retinal degeneration and glaucoma.[2] Myopia should be viewed as a progressive condition associated with the potential risk of vision loss. Moreover, the prevalence of myopia is increasing in Asian urban regions where 80% of teenagers are myopic.[3] Myopia management has a high impact on public health, and finding effective strategies to slow myopia progression should be a priority.

A variety of optical devices and visual strategies have been developed to address central vision but with a reduced or limited effect. For example, undercorrection actually increases the rate of myopia progression.[4–6] Bifocal and multifocal lenses have a limited effect.[7] Some studies have shown promising results in children with rapid myopia progression, with higher success in patients with esophoria at near and higher accommodative lag (LAG).[8] Underaccommodation, that is, LAG, is quantified as the difference between the dioptric level of the accommodative stimulus and the measured accommodative response. Larger LAG, in association with near work, which induces retinal blur at near, has been proposed as a factor in myopia development and progression.[9] Although progressing myopes show larger LAG,[10] attempts to slow myopia progression through plus lens correction at near to reduce or eliminate near vision blur have obtained only modest results in children.[11] Otherwise, a recent study related retinal superior myopic defocus induced by progressive addition lenses with less central myopia progression.[12]

Orthokeratology (OK) is currently the most effective optical method to slow myopia progression.[13–17] Several authors have shown the great impact of OK on the peripheral retinal image,[18,19] with movement of the peripheral image shell forward, which was described as the cause of the myopia control effect.[20] Peripheral hyperopic refraction is believed responsible for myopia development, as the ocular growth mechanism tries to compensate for the imposed peripheral defocus with further elongation even in the presence of a perfectly focused central image.[21,22] There has been more interest in peripheral refraction (PR) after animal studies showed an emmetropization response to specific visual manipulation, with myopia being the result of both spatial form deprivation and imposed hyperopic defocus.[23] The peripheral retina itself can recover or induce myopia,[24,25] especially in monkeys, indicating that the emmetropization process may be controlled actively by the optically modified peripheral image.[26] Myopic eyes have greater relative peripheral hyperopia,[27–29] a characteristic that appears approximately 2 years before the onset of myopia.[30]

From the Department of Optometry (J.P.), Centro Médico Teknon, Barcelona, Spain; Department of Optics and Optometry (S.T., J.A., L.Q.), Polytechnic University of Catalonia—Barcelona Tech, Spain; and Clinical & Experimental Optometry Research Lab (CEORLab) (J.M.G.-M., M.F.-R.), Department and Center of Physics, University of Minho, Braga, Portugal.

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Address correspondence to José M. González-Méijome, Ph.D., Clinical & Experimental Optometry Research Lab, Department of Physics (Optometry), University of Minho, 4710-057 Braga, Portugal; e-mail: jgmeijome@fisica.uminho.pt

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Despite evidence in animals, unfortunately, some studies in humans have shown that baseline PR does not predict or play a significant role in the subsequent onset of myopia or affect myopia progression.[31,32] Indeed, it had been proposed that the peripheral error profiles in myopes may merely be a consequence of ocular growth rather than have a causative role.[33] However, some correlation between changes in PR and central shift has been found in the nasal visual field,[34] and stable and progressing myopes showed significantly different characteristics in their peripheral retinal shape and astigmatic components of tangential and sagittal power errors.[35]

Another theory for myopia onset is related to optical higher-order aberrations (HOAs). Some investigators have tried to gain an understanding of the role of optical quality changes by OK in reducing the rate of axial growth. Eyes with less axial elongation over the treatment period showed a greater increase in coma-like aberrations.[36] Despite the authors' statement, that study did not link both findings. Other HOAs, especially spherical aberration (SA), have been related to LAG. When the eye is choosing the best image plane,[37] myopes generally are less sensitive to negative than positive defocus, which can be linked to their HOA pattern.[38]

According to the peripheral hyperopic defocus theory for myopia control, several approaches have used soft contact lenses with modified optics to change the PR and the myopia progression was arrested by 34%[39] to 50%.[40] A more recent study related the treatment effect with wearing time.[41] Analyses of the optics of the monofocal and bifocal lenses[42,43] and related PR changes have been reported,[44] but no studies have shown in the effects of such lens designs on LAG, HOAs, and PR. Contact lenses with radial refractive gradient are able to change the peripheral refractive pattern. However, they also impact the pattern of HOAs and, by virtue of the changes in the plane of the best image with regard to the retina, the accommodative lag could change. According to the current knowledge, both paths could interfere with the myopia development. Furthermore, as HOAs have the potential to adversely affect the image quality, it is necessary to ensure that this does not impact significantly the visual quality assessed by the contrast sensitivity function (CSF).

The aim of this study was to simultaneously evaluate the effect of a soft radial refractive gradient (SRRG) contact lens devised to change the PR on accommodative lag, whole eye HOAs, and contrast sensitivity in a population of young myopes. To our knowledge, this is the first study to address these 3 important factors of the theories and justify optically guided regulation of ocular growth in one study.

METHODS

Sample

Sixty-two subjects were recruited from the student population at the Terrassa School of Optics and Optometry (Universitat Politècnica de Catalunya, Terrassa, Spain). After 3 subjects were excluded because of contact lens decentration, 59 subjects (29 men and 30 women) were evaluated. The inclusion criteria were myopia with a spherical equivalent (SE) refraction ranging from −0.50 to −7.50 diopters (D) (mean±standard deviation [SD], −2.44±1.71 D) and refractive astigmatism below −0.75 D (−0.19±0.33 D), age between 18 and 25 years, and a best-corrected visual acuity of 20/20 or higher. The exclusion criteria were any ocular disease or use of any systemic or ocular medication that could affect the refractive error or accommodative function. Subjects were required to understand and sign a consent form before study enrollment. The Ethical Committee of Clinical Research of the Centro Medico Teknon, Barcelona, Spain, approved the study protocol, which adhered to the tenets of the Declaration of Helsinki.

Lens

An experimental SRRG contact lens designed to produce peripheral myopic defocus was fitted after a baseline measure was obtained without refractive correction. The lens is comprised of 2-hydroxyethyl methacrylate, with 38% water content (overall diameter, 14.00–15.00 mm; base curve radius, 8.00–8.90 mm). The central thickness varied depending on the optical power of the lens.

The optical design of the experimental lens used parameters for theoretical eyes obtained from Atchison[45] that were incorporated into the Zemax-EE software version 6 (Radiant Zemax, Redmond, WA). The experimental lens has a unique central front and back aspheric optic zone 8 mm in diameter. The lens has a radial refractive gradient, so only the central apical zone has the power required for distance vision, and the aspheric design provides a progressive increasing add power, starting at the central geometric point and providing a +2.00 D add plus power 1.9 mm from the center (3.80-mm chord diameter) corresponding to approximately 30 degrees of retinal eccentricity and achieving approximately +9.5 D at the edge of the optical zone (8-mm chord diameter). The contact lens was fitted according to the subjective refraction, corneal curvature, and visible iris diameter. The corneal topography was measured using the Pentacam (Oculus, Wetzlar, Germany). Adjustments to the final prescription were based on spherical overrefraction, and a new lens was ordered if discrepancies over ±0.25 D occurred. Fitting was assessed for centration on lateral gaze movements using the slitlamp beam. All lenses were within the desired limits of less than 0.25 to 0.50 mm of decentration on blink in upgaze and 0.50- to 1.00-mm displacement during horizontal excursion on lateral gaze. These values are considered acceptable good fitting parameters for modern soft contact lenses.[46] During the study visit, the lenses were allowed to settle for 20 to 30 min to equilibrate and stabilize on the ocular surface and for subjects to feel sufficiently comfortable to undergo the examination. Measurements were obtained without correction for PR and aberrations and with the best spectacle correction in a trial frame at 12 mm for CSF.

Peripheral Refraction

Measurements of the central and peripheral (off-axis) refraction were obtained with an open-field Grand Seiko Auto-Refractometer/Keratometer WAM-5500 (Grand Seiko Co, Ltd, Hiroshima, Japan) up to 30° in the nasal and temporal horizontal retina in 5-degree steps. This instrument and its other commercial brand that uses the same technology for refractive error measurement (Shin-Nippon) have been used reliably for foveal[47,48] and PR measurements.[49,50] In this study, a laser system was mounted on the subject's head and aligned with the central fixation point in primary gaze. The PR was measured with head rotation to ensure that the lens did not move from the resting position in primary gaze. To measure head rotation, the laser had to coincide with a series of markings on the wall 2.5 m in front of the subject. This created a limitation on the range of field measured, making it measurable up to 30°. The left eye was occluded during the measurements to avoid misalignments under binocular fixation. Measurements were conducted under noncycloplegic conditions. Descriptive statistics (mean±standard deviation) were calculated for the refraction vector components as SE, $M=Sph+Cyl/2$, horizontal component of astigmatism, $J0=-Cyl\cdot\cos(2\alpha)/2$, and oblique component of astigmatism, $J45=-Cyl\cdot\sin(2\alpha)/2$ according to Fourier analysis, as recommended by Thibos et al.,[51] where Sph, Cyl, and α are the manifest sphere, cylinder, and axis, respectively. M, J0, and J45 were calculated from the mean clinical refraction resulting from 5 consecutive readings obtained at each visual field eccentricity and were considered for statistical analysis. The relative peripheral refractive error was calculated by subtracting the central M, J0, or J45 value obtained at the fovea from that obtained at each eccentric retinal location. Sagittal and tangential foci were calculated according to the following equations: $Fs=M-J0$ and $Ft=M+J0$. Peripheral measurements were performed using the pupillary center for alignment.

Accommodation Lag

The accommodation lag was measured monocularly in the right eye using the Grand Seiko WAM-5500 autorefractor through the SRRG lens at distance and near for a target consisting of a line of a high-contrast reading card of 20/40 letters. The near stimulus was placed at 40 cm, which represents a 2.50 D accommodative demand. The letter size at near was changed to keep the visual angle the same as the target at 2.50 meters. The luminance was 20 cd/m^2 for both targets. Five readings were measured in each position, and during the measurements the subject fixated on one letter target. The sphere and cylinder were recorded for each measurement, and then the mean SE for the set of measurements was calculated. The accommodation lag was calculated by subtracting the mean measured accommodative response from far to near SE and then subtracting it from the accommodative stimulus following the procedures described by He et al.[52] Sustained accommodative effort has been suggested as a potential etiological factor for myopia progression.[53]

Optical Quality and Visual Performance

The optical quality of the eye was assessed using an Irx3 Hartmann-Shack aberrometer (Imagine Eyes, Orsay, France). Higher-order aberrations from the third to sixth order were obtained in dim light conditions under natural mydriasis with a 5-min adaptation time to assure the largest natural pupil. Additionally, a limitation for 3- and 5-mm pupillary sizes was done using the software in the instrument. Changes in the root mean square (RMS) from baseline without the lens for spherical-like HOAs (including Zernike polynomials Z_4^0 and Z_6^0), coma-like HOAs (including Zernike polynomials Z_3^{-1}, Z_3,^{1} Z_5^{-1}, and Z_5^1), trefoil (including Zernike polynomials Z_3^{-3}, Z_3^3), secondary astigmatism (including Zernike polynomials Z_4^{-2}, Z_4,^{2} Z_6^{-2}, and Z_6^2), and total HOAs were considered for statistical analysis.

Visual performance was assessed through the CSF using a CVS-1000 E (VectorVision, Dayton, OH) for spatial frequencies of 1.5, 3, 6, 12, and 18 cycles/degree (c/d) with the patient at 3 meters under photopic (105 cd/m^2) and low mesopic (0.6 cd/m^2) conditions.

The visual acuity was measured with the Logarithmic 2000 series Early Treatment Diabetic Retinopathy Study chart at 4 meters (Precision Vision, La Salle, IL).

Statistical Analysis

The SPSS software package version 19 (SPSS Inc., Chicago, IL) was used for statistical analysis. The Kolmogorov–Smirnov test was applied to evaluate the normality of the data distribution. The paired Student *t* test or Wilcoxon signed-rank test for two related samples was used to analyze the statistical significance of the differences between contact lenses versus baseline depending on the normal or nonnormal distribution. The Pearson or the Spearman rho correlation tests was also used to determine the relationship between aberrations and CSF. $P<0.05$ was considered statistically significant.

RESULTS

Relative Peripheral Refraction

The relative peripheral refractive error mean values expressed as M, J0, J45, sphere, and cylinder, respectively, underwent significant changes with the lens in place compared with baseline. Significant changes were observed from 30 to 15° temporally and 30° nasally in the M value. J0 showed significant changes from 30 to 20° temporally and 30° nasally (with a significantly opposed value at 15° nasally) and any of all J45 values was significant (Figs. 1, 2). Looking at both astigmatic foci (sagittal and tangential), we observed that the lens significantly changes the peripheral astigmatic refraction toward more myopia in the temporal retina (from 30° to 15° in the temporal retina and from 30° to 25° in the nasal retina) (Fig. 3). The sagittal focus remains hyperopic for most of the peripheral visual field even while the lens is worn.

Significantly different values from 30° to 20° in the temporal retina were found for sphere foci. Cylinder foci were significant

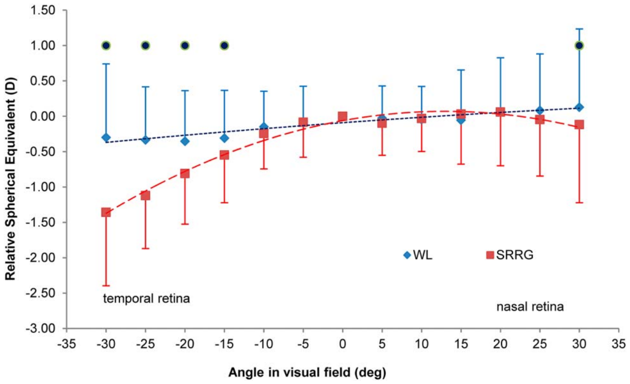

FIG. 1. Relative peripheral refractive error (peripheral minus center) in mean spherical equivalent values (M) as a function of angle in the temporal retina (negative values) and nasal retina (positive values) across 70 degrees of the horizontal visual field. Experimental conditions are represented without the lens (◆) and with the radial refractive gradient (■) lens. The bars represent the standard error of the mean, half of that is suppressed and a polynomial function of second degree was fitted for each experimental situation for a better interpretation of the refractive profile across the horizontal visual field. The black dots indicate the locations with significant ($P<0.05$) differences. SRRG, soft radial refractive gradient; WL, without lens.

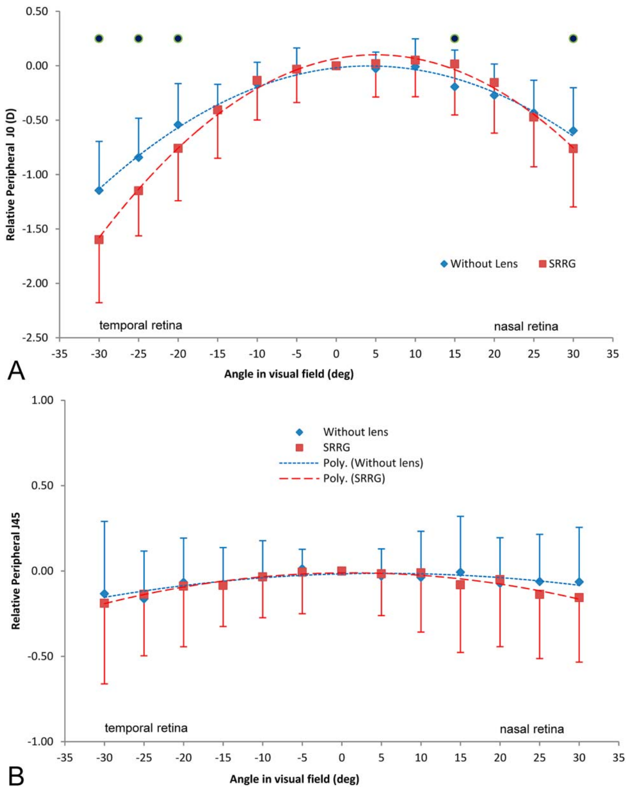

FIG. 2. Relative peripheral J0 (A) and J45 (B) for both experimental conditions, without the lens (◆) and with the SRRG lens (■). The bars represent the standard error of the mean, half of which have been eliminated for clarity and a polynomial function of second degree was fitted for each experimental situation for a better interpretation of the refractive profile across the horizontal visual field. The black dots indicate the locations with significant ($P<0.05$) differences. SRRG, soft radial refractive gradient.

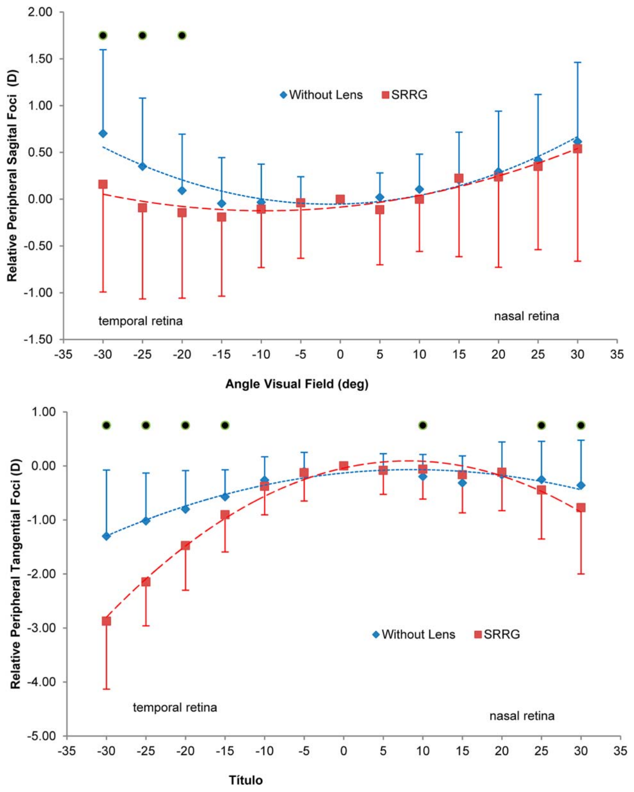

FIG. 3. Relative peripheral sagittal foci and tangential foci for both experimental conditions without the lens (◆) and with the SRRG lens (■). The bars represent the standard error of the mean, half of which have been eliminated for clarity and a polynomial function of second degree was adapted for each experimental situation for a better understanding. The black dots indicate the locations with significant ($P<0.05$) differences. SRRG, soft radial refractive gradient.

from 30° to 15° temporally and from 30° to 25° in the nasal retina (with a significantly opposed value at 10° nasally). Myopization increased with eccentricity in these values that corresponded to the difference without lenses and with the experimental contact lens used in the study. Table 1 shows the specific values.

Visual Acuity and Contrast Sensitivity Function

Comparison of the visual acuity with and without lenses showed no significant difference in either condition ($P>0.0999$), indicating that the experimental lenses showed no effect on visual acuity.

The CSF differed significantly in the 6 c/d frequency under photopic conditions, with a loss of -0.08 ± 0.25 (log) with the experimental lens ($P<0.05$). The scotopic conditions resulted in a significant sensitivity loss at 6 and 12 c/d (mean difference, -0.15 ± 0.25, $P<0.05$ and -0.14 ± 0.29, $P<0.05$ log units, respectively).

Aberrations

All HOAs, including trefoil, coma-like, SA, and secondary astigmatism, increased with the SRRG lens compared with no lens ($P<0.05$). This effect was particularly marked for the 5-mm pupillary size rather than the 3-mm pupils. Significant differences were seen with the SRRG lens for the 3-mm pupil compared with baseline and for the 5-mm pupil ($P<0.05$, for all orders of aberration). The third (Z_3^1 and Z_3^{-1}) and spherical-like RMS (Z_4^0 and Z_6^0) showed the largest differences (Fig. 4).

Spherical Aberrations and Contrast Sensitivity Function Relations

We obtained negative significant correlations between SA and CSF at 3-mm pupil diameter for the following spatial frequencies: 3 c/d ($r=-0.308$; $P<0.05$), 6 c/d ($r=-0.545$; $P<0.001$), 12 c/d ($r=-0.495$; $P<0.001$), and 18 c/d frequency ($r=-0.420$; $P<0.005$). For secondary astigmatism, we found a weak negative significant correlation ($r=-0.281$; $P<0.05$). Under 5-mm pupil conditions, results showed significant negative correlations for all the CSF frequencies: 3 c/d ($r=-0.371$; $P<0.05$), 6 c/d ($r=-0.423$; $P<0.005$), 12 c/d ($r=-0.463$; $P<0.001$), 18 c/d ($r=-0.478$; $P<0.0001$), and SA. Coma-like HOAs showed significantly negative correlations for 6 and 12 c/d ($r=-0.347$; $P<0.05$ and $r=-0.377$; $P<0.005$) and secondary astigmatism for the frequencies of 12 and 18 c/d ($r=-0.369$; $P=0.008$ and $r=-0.311$; $P<0.05$), respectively.

Accomodation Lag

With the lens on the eye, the accommodative lag decreased significantly ($P=0.0001$) compared with no lens. The mean values

TABLE 1. *Relative Peripheral Refractive Error (Peripheral Defocus Minus Central Defocus) as Spherical Equivalent Values (M±SD), Cylinder Power Set at Orthogonally 90° and 180° Meridians (J0±SD), Representing Cartesian Astigmatism*

RPRE	M			J0		
	WL	SRRG		WL	SRRG	
Location	Mean±SD	Mean±SD	Sig (*p*)	Mean±SD	Mean±SD	Sig (*p*)
30T	−0.29±0.93	−1.34±1.05	**0.001**	−1.14±0.44	−1.59±0.58	**0.001**
25T	−0.33±0.69	−1.10±0.77	**0.001**	−0.84±0.36	−1.15±0.41	**0.001**
20T	−0.35±0.57	−0.79±0.73	**0.001**	−0.54±0.38	−0.76±0.48	**0.002**
15T	−0.31±0.41	−0.53±0.69	**0.019**	−0.40±0.23	−0.40±0.45	0.955
10T	−0.15±0.37	−0.22±0.51	0.217	−0.16±0.20	−0.13±0.36	0.526
5T	−0.07±0.27	−0.06±0.50	0.840	−0.03±0.19	−0.03±0.31	0.966
5N	−0.03±0.22	−0.07±0.47	0.491	−0.03±0.15	0.02±0.31	0.324
10N	−0.05±0.31	−0.01±0.46	0.527	−0.01±0.26	0.05±0.34	0.262
15N	−0.05±0.33	0.05±0.70	0.211	−0.19±0.34	0.02±0.47	**0.003**
20N	0.07±0.27	0.08±0.77	0.879	−0.27±0.29	−0.15±0.46	0.089
25N	0.08±0.63	−0.03±0.80	0.148	−0.43±0.30	−0.47±0.46	0.537
30N	0.13±0.75	−0.10±1.11	**0.047**	−0.60±0.39	−0.76±0.54	**0.041**

RPRE	J45			Fs			Ft		
	WL	SRRG		WL	SRRG		WL	SRRG	
Location	Mean±SD	Mean±SD	Sig (*p*)	Mean±SD	Mean±SD	Sig (*p*)	Mean±SD	Mean±SD	Sig (*p*)
30T	−0.13±0.42	−0.19±0.47	0.393	0.85±0.75	0.24±1.04	<**0.001**	−1.44±1.25	−2.96±1.32	<**0.001**
25T	−0.11±0.28	−0.14±0.36	0.551	0.51±0.58	0.03±0.88	<**0.001**	−1.18±0.94	−2.27±0.83	<**0.001**
20T	−0.07±0.26	−0.09±0.35	0.652	0.19±0.63	−0.05±0.87	**0.015**	−0.89±0.73	−1.57±0.85	**0.001**
15T	−0.08±0.22	−0.08±0.24	0.824	0.09±0.40	−0.14±0.97	0.077	−0.71±0.53	−0.95±0.61	0.008
10T	−0.04±0.22	−0.03±0.24	0.900	0.02±0.38	−0.11±0.71	0.178	−0.32±0.45	−0.38±0.51	0.367
5T	0.01±0.11	−0.01±0.24	0.529	−0.04±0.36	−0.05±0.67	0.965	−0.10±0.29	−0.11±0.48	0.880
5N	−0.03±0.16	−0.02±0.24	0.726	0.00±0.28	−0.12±0.66	0.241	−0.05±0.26	−0.08±0.41	0.694
10N	−0.04±0.27	−0.01±0.35	0.639	−0.04±0.40	−0.08±0.58	0.608	−0.05±0.40	0.02±0.57	0.269
15N	−0.01±0.33	−0.08±0.40	0.201	0.14±0.59	0.02±0.87	0.265	−0.25±0.51	0.05±0.83	**0.005**
20N	−0.07±0.27	−0.05±0.39	0.662	0.34±0.61	0.22±0.97	0.328	−0.21±0.66	−0.09±0.81	0.311
25N	−0.06±0.28	−0.14±0.38	0.136	0.51±0.64	0.43±0.88	0.388	−0.35±0.75	−0.52±0.96	0.078
30N	−0.06±0.32	−0.16±0.38	0.078	0.72±0.80	0.64±1.16	0.589	−0.47±0.89	−0.88±1.30	**0.003**

Negative values of J0 indicate against-the-rule astigmatism; positive values of J0 indicate with-the-rule astigmatism. Oblique astigmatism (J45±SD), referred to a cross-cylinder set at 45° and 135°, refractive sphere foci (Sph±SD) and cylinder refractive foci (Cyl±SD) representing the foci of the sum of sphere plus negative cylinder. Sagittal foci (Fs) and tangential foci (Ft) are related to relative peripheral astigmatic components at 90° and 0°.

Negative values of Ft indicate forward vertical foci position related to Fs foci. Values are expressed in diopters (D).

p represents the value of statistical significance according to *Paired Sample t test*. Bold indicates statistically significant power difference compared with central point (95% confidence interval).

N, nasal side of retina; RPRE, relative peripheral refractive error; SRRG, soft radial refractive gradient; T, temporal side of retina; WL, without lens.

with and without the lens were 0.37±0.42 and 0.64±0.28 D, respectively. The difference between the mean values (0.28±0.40 D) was larger than the minimal detectable difference in clinical circumstances. Figure 5 represents the correlation between accommodative lag and axial myopia under both experimental conditions (without and with contact lens).

DISCUSSION

The experimental SRRG contact lens modified the peripheral refractive shell profile by moving it forward in the young myopic eyes in this study. A study of a large sample of children with myopia reported a mean of +0.80±1.29 D for the relative hyperopic relative PR at 30° in the temporal peripheral retina.[54] Therefore, the change we found in the M value of −1.07 D at 30° axis in the peripheral temporal retina (nasal visual field) may be sufficient to modify the position of the image shell, placing it in front of the retina in the average eye.

We observed significant differences through the naked eye and when the SRRG lens was worn in the SE value measurements at 30°, 25°, 20°, and 15° in the temporal retina but only at 30° in the nasal retina. Figure 1 shows the mean±SD relative peripheral SE at each retinal location. One reason for this result may be related to a normal tendency for soft lenses to move temporally off-center in addition to the nasal position of the visual axis with respect to the optical axis (angle kappa). Wolffsohn et al.[46] reported a mean lens decentration of 0.07±0.14 mm horizontally (temporal) compared with the center of the cornea, and Dominguez-Vicent et al.[55] reported a displacement of the axis due to the angle kappa of 0.43±0.13 mm using the Orbscan (Bausch & Lomb, Rochester, NY). The sum of the 2 accounts for the temporal position of the optical center of the lens with respect to the optical axis, which may correspond to a 6- to 10-degree axis error depending of the eye model used.[56–58] In other words, usually a progressive center distance soft lens induces more addition power on the temporal retina because of this decentration effect and might explain the bigger effect of the temporal retina also reported previously.[39,59,60] Moreover, a recent study of new soft contact lens for designed myopia control evaluated a lens with a decentered optical zone that was shifted 0.5 mm nasally from the geometrical center of the lens

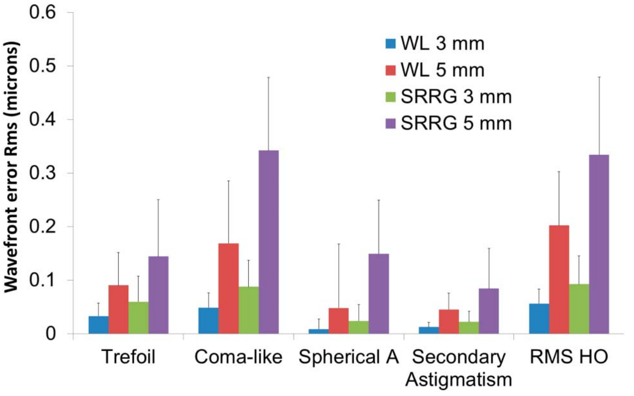

FIG. 4. Higher-order aberrations without the lens and with the experimental SRRG lens expressed as trefoil, spherical-like aberrations, coma-like aberrations, secondary astigmatism, and HOA for 3- and 5-mm pupillary sizes. HOA, higher-order aberration; SRRG, soft radial refractive gradient; WL, without lens.

to be coincidental with the optical center of the lens with the pupillary center. The results on myopia control with this lens did not reach significance, perhaps because of the lower peripheral progressive addition of +0.50 D.[61] A possible misallocation error due to the head of the patient when looking at the fixation point could be avoided by turning the eye only, as a recent study[62] has shown that, when two multifocal lenses were tested in the horizontal visual field, values did not change significantly when measured during rotation of the eye or head.

The nasal half of the retina may be more important regarding the mechanism of ocular growth control because Faria-Ribeiro et al.[35] reported a difference between a progressing group and a nonprogressing group of young myopic subjects; the patients in the progressing group experienced more hyperopic relative astigmatic defocus than the nonprogressing group in the nasal retina. If the peripheral retina is responsible for the ocular growth changes, the relationship between the blur for the "tangential" and "radial" neurons may control growth.[38] The blur detected for these neurons differs because of oblique astigmatism, which places the foci lines close to the vertical and horizontal meridians.[63] In this sense, we found a significant difference in the astigmatic component J0 but not in J45 such as that seen in Figure 2A, B, respectively.

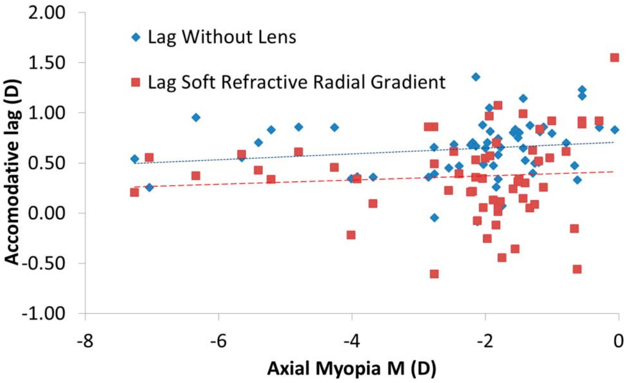

FIG. 5. Accommodative lag with and without the SRRG lens. Two regression lines are plotted. The dotted line represents no lens, and the dashed line represents the experimental lens. SRRG, soft radial refractive gradient.

In the peripheral retina, oblique astigmatism increases and produces two main foci lines. This has been calculated for our patients by obtaining the sagittal and tangential foci. Similar results have been found recently in OK patients, particularly in lower myopes.[64] Howland proposed that astigmatism acts as a unique visual cue to detect the position of the foci with respect to the retina,[65] but its role on axial elongation of the eye remains unclear. Adding to this uncertainty is the potential effect of different types of off-axis astigmatism on the central refraction.[1,66] However, in the presence of two focal lines, the retina tends to use the more myopic plane of the two lines to guide eye growth. In monkeys treated with dual-focus lenses, refractive development was dominated by the more anterior (i.e., relatively myopic) image plane. In this respect, a series of studies have shown that myopic defocus seems to have a stronger effect on ocular growth than hyperopic defocus.[67] The results in monkeys with imposed dual-focus lenses showed that imposing relative myopic defocus directed refractive development in most cases toward the more myopic/less hyperopic focal plane (i.e., the more anterior focus).[68] This seems to agree with the results found in OK where myopization effect is mainly obtained at the expense of the tangential focus.[64] Otherwise, if the more emmetropic astigmatic plane is preferred, the consolidated efficacy of OK to regulate myopia progression[69] could not be justified.

We need to be aware that a decentered optical zone may increase optical multifocality because this places in front of the pupil different power zones of the lens that increase aberrations, mainly coma. In this study, we found that the lens significantly increased the coma-like, spherical-like, secondary astigmatism, and total HOAs. We reported similar results with a previous soft peripheral gradient design using the same concept.[70] According to another previous experiment that we conducted, the design of the current lens manufactured with a rigid gas-permeable material caused even stronger changes in peripheral myopization.[71] Among them, the coma-like aberration showed a greater change. However, the potential involvement of coma-like aberrations as a regulatory effect over ocular elongation that has been suggested[36] remains to be demonstrated.

Regarding contrast sensitivity, the experimental lens significantly decreased CSF under photopic conditions only at the 6 c/d frequency and worsened all the studied frequencies under scotopic conditions, except for 18 c/d, which remained unchanged. Accordingly, this SRRG treatment lens degrades the foveal image especially in dim light. Nonetheless, because the visual acuity was measured under photopic conditions and for high contrast charts, we did not observe a decrease in this metric. We found a significant negative correlation between the SA and CSF without lenses at 6, 12, and 18 c/d in 3- and 5-mm pupils but no correlation between the HOAs induced by the lens and CSF. This may be related to a particular change in the HOAs for each individual. Moreover, it may suggest that the associated reduction in image quality may promote axial myopia in a way similar to form deprivation, which is a graded phenomenon.[72] However, the results of animal studies with multifocal or dual-focus lenses indicated that despite a resulting reduction in image contrast the lenses slow axial grow.[73]

Finally, we found a significant reduction in accommodation lag when patients were evaluated with the experimental soft contact lens (Fig. 5). In fact, some studies have shown that induced changes in ocular SA by OK decrease the accommodation lag,[37] in contrast with other investigators who found no change[74] possibly because of different methodology.

Lead and accommodation lag of accommodation are affected by ocular HOAs, with significant correlations with the peak of the visual Strehl ratio based on the modulation transfer function.[75] It seems plausible that the higher accommodation lag seen in myopes provided optimized retinal image characteristics.[76] Visual contrast is greater when Zernike coefficients Z_2^0 and Z_4^0 of the eye and lens system have opposite signs. A positive SA present in myopia control treatments such as OK and radial refractive gradient lenses combined with myopic blur has the potential to reduce the accommodation lag placing the best plane image in front of the retina.[38,77] Because the amount of positive SA declines with accommodation and becomes steadily more negative with further accommodation,[78] the increase in positive SA with the current lens may protect against negative SA and hyperopic blur that will situate the best plane image behind the retina, resulting on a higher accommodation lag and worsening the peripheral defocus.[77] A limitation of this study was that we did not measure the SA under accommodation to validate this theory.

High accommodation lag is considered a factor in the pathogenesis of myopia because of the association between myopia progression and near work.[79] Further analyses with progressive addition and bifocal spectacle lenses that potentially reduce the defocus at near showed larger treatment effects in individuals with larger accommodation lag in combination with near esophoria.[80,81] However, larger accommodation lag has been linked to development[82] and progression of myopia.[83] Although there is no unanimous agreement across studies, some have indicated a tendency for myopic children to have a larger accommodation lag compared with emmetropes.[80,52] However, hyperopic defocus from accommodation lag, therefore, may be more of a consequence than a cause of myopia.[83]

In conclusion, the SRRG contact lenses showed potential to change significantly the PR in the myopic direction, particularly in the temporal retina. Furthermore, the accommodation lag was decreased with the experimental lens. Both factors might be effective to interfere with regulation of axial elongation in myopic eyes, without significant visual compromise as observed by visual acuity and CSF. However, a longitudinal study is needed to clarify the effect of all those factors and their relative weight in myopia progression.

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