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TECHNICAL NOTE

Evaluating the peripheral optical effect of multifocal contact lenses

Robert Rosén[1], Bart Jaeken[2], Anna Lindskoog Petterson[3], Pablo Artal[2], Peter Unsbo[1] and Linda Lundström[1]

[1]Biomedical & X-Ray Physics Royal Institute of Technology (KTH), Stockholm, Sweden, [2]Laboratorio de Optica, Universidad de Murcia, Murcia, Spain, and [3]Unit of Optometry, Karolinska Institute, Stockholm, Sweden

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Correspondence: Linda Lundström
E-mail address: linda@biox.kth.se

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Abstract

Purpose: Multifocal soft contact lenses have been used to decrease the progression of myopia, presumably by inducing relative peripheral myopia at the same time as the central image is focused on the fovea. The aim of this study was to investigate how the peripheral optical effect of commercially available multifocal soft contact lenses can be evaluated from objective wavefront measurements.

Methods: Two multifocal lenses with high and low add and one monofocal design were measured over the ±40° horizontal field, using a scanning Hartmann–Shack wavefront sensor on four subjects. The effect on the refractive shift, the peripheral image quality, and the depth of field of the lenses was evaluated using the area under the modulation transfer function as the image quality metric.

Results: The multifocal lenses with a centre distance design and 2 dioptres of add induced about 0.50 dioptre of relative peripheral myopia at 30° in the nasal visual field. For larger off-axis angles the border of the optical zone of the lenses severely degraded image quality. Moreover, these multifocal lenses also significantly reduced the image quality and increased the depth of field for angles as small as 10°–15°.

Conclusions: The proposed methodology showed that the tested multifocal soft contact lenses gave a very small peripheral myopic shift in these four subjects and that they would need a larger optical zone and a more controlled depth of field to explain a possible treatment effect on myopia progression.

Introduction

Peripheral optical errors have been suggested to influence the development of myopia.[1,2] This study suggests a methodology to evaluate the optical effect of multifocal soft contact lens designs on the image quality over the peripheral retina. Myopia is the condition in which the refractive power of the eye is too strong relative to its length. It is normally caused by the eye growing too long[1–4] and is associated with increased risk of ocular diseases.[5] Currently, the prevalence of myopia is increasing, likely due to changes in the everyday visual environment.[1,2,6] Defocus of the retinal image is one such important environmental factor, as demonstrated by animal studies (see e.g. the review by Wildsoet[7]). Furthermore, the sign of peripheral defocus has also been shown to play a role; even with a clear foveal image, peripheral hyperopia (i.e. an image behind the retina) induces central myopic growth.[8] It is likely that a similar regulation process takes place in the human eye, though the association between relative peripheral hyperopia and myopia progression is weak.[9] Nevertheless, there is considerable interest in correction methods that allow manipulation of the peripheral image while leaving the foveal image unaltered. One option currently being tested is to use multifocal and bifocal soft contact lenses with a centre distance design.[10–16] Two recent studies using lenses with 2 D add have reported a reduction in myopia progression from −0.86 to −0.57 D per year and from −0.69 to −0.44 D per

10 months respectively.[11,12] In these lenses, the power of the inner zone corrects for the foveal refractive errors whereas the outer zone power is chosen to be more positive. Such lenses are commercially available today, though most of them are not designed to prevent myopia, as they are marketed towards presbyopic patients. However, interest in the research community in these lenses goes beyond their marketed purpose, since the more positive outer zone can reduce accommodative lag as well as impose myopia on the peripheral retina and thereby possibly inhibit myopia development. Bifocal and multifocal contact lenses also have the advantage that they can be manufactured with a central (distant) power of zero dioptres and thereby be worn by emmetropic eyes, who might be at risk of becoming myopic, as well as by already established myopes.

However, multifocal designs inevitably affect the quality of the image, which might decrease the effective peripheral image shift of the lens. To our knowledge there is no study on the full off-axis optical image quality with bifocal or multifocal contact lenses, and only one on monofocal lenses.[17] Previous investigations on multifocal lenses have only reported the change in relative peripheral defocus (RPD, i.e. the difference between foveal and peripheral refractive state) derived from lower order aberrations.[11,16,18] In the present study we therefore suggest some additional objective metrics to evaluate the change in peripheral optical quality when wearing multifocal soft contact lenses; higher order root mean square wavefront error (RMS), the normalised area under the modulation transfer function (MTF), the depth of field, as well as the RPD that optimises the area under the MTF. We apply these metrics on peripheral wavefront measurements performed over the 80° horizontal field of four subjects wearing commercially available multifocal soft contact lenses with two different add powers and two designs. We are especially interested in whether the lenses actually are changing the RPD, whether overall image quality beyond defocus is altered, and over which parts of the visual field these effects take place.

Methods

Subjects, contact lenses and measurements

Multifocal soft contact lenses were fitted by an experienced optometrist and were worn for 20 min before measurement in the right eye of four subjects; three emmetropes and one low myope (average on-axis spherical refractive error equal to −0.7 D, ranging from +0.50 to −2.75 D, no cylinder, 25–39 years). The subjects were measured with the lenses described in *Table 1*; PureVision$^{\text{TM}}$ a monofocal lens design with spherical aberration control (i.e. inducing negative c_4^0), Proclear Multifocal N$^{\text{TM}}$ a centre near design with the more positive power in the centre of the lens, and Proclear Multifocal D$^{\text{TM}}$ a centre distance design with the more positive power in the outer zone of the lens. The multifocal lenses were evaluated both with +1 and +2 dioptres add. All subjects were measured with lenses that included their foveal refractive correction. As a baseline, they were also measured without wearing any lens.

The peripheral optics of the subject's right eye was evaluated with the new fast scanning Hartmann–Shack sensor especially developed for off-axis wavefront measurements at the Laboratory of Optics in Murcia, Spain.[19,20] The sensor has an open field of view and uses near infrared light (780 nm) to be as comfortable as possible for the subject. The aberrations over the horizontal peripheral field were measured out to ±40° with an angular resolution of 1°. For each lens, four sweeps were made within 7.2 s while the subject was stabilised with a chin rest and maintained fixation to a 2° Maltese cross placed at a distance of 2 m. The order of the lenses was random. The measurements were made in dim light with natural pupils (no cycloplegia) and subjects were allowed to blink. The study followed the tenets of the Declaration of Helsinki and informed consent was obtained from the subjects beforehand.

Data analysis

The wavefronts were reconstructed with Zernike coefficients[21] defined over a circular aperture inscribing the elliptical pupil (the LC method proposed by Lundström *et al.*[22]). To allow comparison, the data for all measurements were then shrunk to a pupil diameter of 4 mm, which was smaller than the minor pupil diameter of all subjects (corresponding to the SC method by Lundström *et al.*[22], algorithms given by Lundström and Unsbo[23]). No correction for chromatic aberration was performed. The four sets (one from each sweep) of Zernike coefficients in each eccentricity for each person and lens were averaged and the wavefront aberrations were then analyzed in two different ways:

First, to allow comparison with other studies, we used the methodology to calculate defocus directly from the second order Zernike coefficients (i.e. mean spherical equivalent $M = -4\sqrt{3} \cdot c_2^0/r_{\text{pupil}}^2$). This metric minimised the RMS of the wavefront over the whole 4 mm circular aperture.

However, minimising the RMS is known to be a poor predictor of the subjective refraction, even for foveal measurements (see e.g. the study by Thibos *et al.*[24]). In the periphery, where the aberrations are larger and the pupil is elliptical, it is especially useful to determine defocus using image quality metrics that correspond with subjective refraction.[25] We therefore also calculated defocus with an image quality metric similar to AreaMTF in the study by Thibos *et al.*[24]: The MTF out to 10 cycles per degree was

Table 1. The measured lens designs

Design	Add	Brand	Manufacturer	Base curve (mm)	Optical zone (mm)	Material
Monofocal	–	PureVision^{TM}	Bausch & Lomb	8.6	8.9	Balafilcon A
Centre near	+1.0 and +2.0 D	Proclear Multifocal N^{TM}	Cooper Vision	8.7	8.5	Omafilcon A
Centre distance	+1.0 and +2.0 D	Proclear Multifocal D^{TM}	Cooper Vision	8.7	8.5	Omafilcon A

calculated using Fourier transformation and then averaged over all orientations. The elliptical shape of the pupil was preserved in these calculations (but reduced in scale with the radius of the major axis equal to 2 mm). The area under the one dimensional MTF was then normalised with the diffraction limited case. The value of this metric at best spherical correction was also used as a measure of the retinal image quality and the depth of field was taken as the dioptric distance between the limits imposed by the defocus that reduced the area to 80% of the maximal area, as proposed by Marcos.[26]

Results

Optical zone limitation

To determine at which angle the border of the optical zone of the contact lens started to degrade the quality of the measurement, manual inspection of the actual spot pattern images was performed. An example of the spot patterns at a few measurement angles can be seen in *Figure 1*. Without any contact lens, the spot patterns did not show any large irregularities all the way out to ±40° (upper row in *Figure 1*). With a contact lens worn, the patterns were generally fine out to 20°–30° in the nasal visual field, and out to 30°–40° in the temporal visual field. For larger angles the border of the optical zone of the lens caused a larger displacement of some spots (indicated by the arrows in the lower row of *Figure 1*). This means that there was an abrupt change in the local refractive power and that the measurement of especially defocus was ambiguous. There was no difference between the monofocal and the multifocal lenses in this regard, both showed affected spot patterns at angles larger than 30°. Thus, defocus results for contact lens data at the outer periphery should be interpreted with caution.

Relative peripheral defocus using traditional RMS metric

As explained in *Methods*, the level of defocus was first calculated directly from the 2nd order Zernike coefficients and the RPD was found by subtracting the foveal mean spherical equivalent from the peripheral. The RPD without lens and with the three different lens designs are displayed separately for the four subjects in *Figure 2*. As can be seen, the RPD without lens (indicated by black filled circles in *Figure 2*) followed the well documented pattern of relative peripheral myopia for the emmetropes.[1,2,20,22,27,28] The monofocal and multifocal centre near designs induced more peripheral hyperopia (or less myopia) compared to the RPD without lens. The largest shift, up to 2 D, was obtained with the centre near lens with high add. The only lens that gave an RPD slightly more myopic than that without lens was the centre distance design with high add; it induced peripheral myopia of about 0.5 D in the nasal visual field, with an even smaller shift on the temporal side.

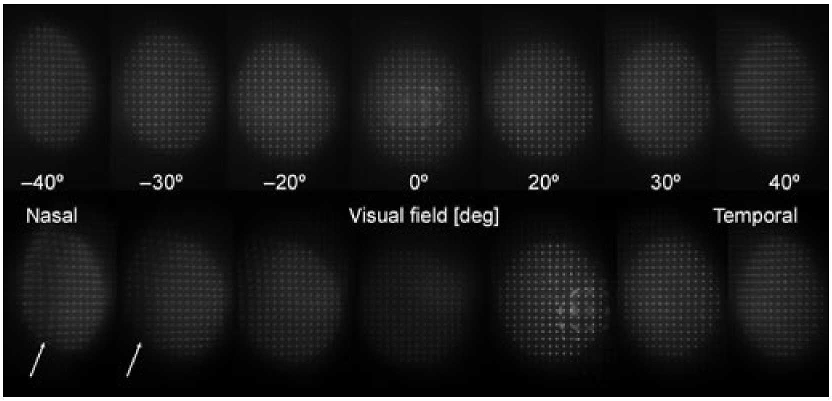

Figure 1. Spot pattern without (top) and with (bottom) a multifocal centre near soft contact lens. Optical zone limit indicated by arrows.

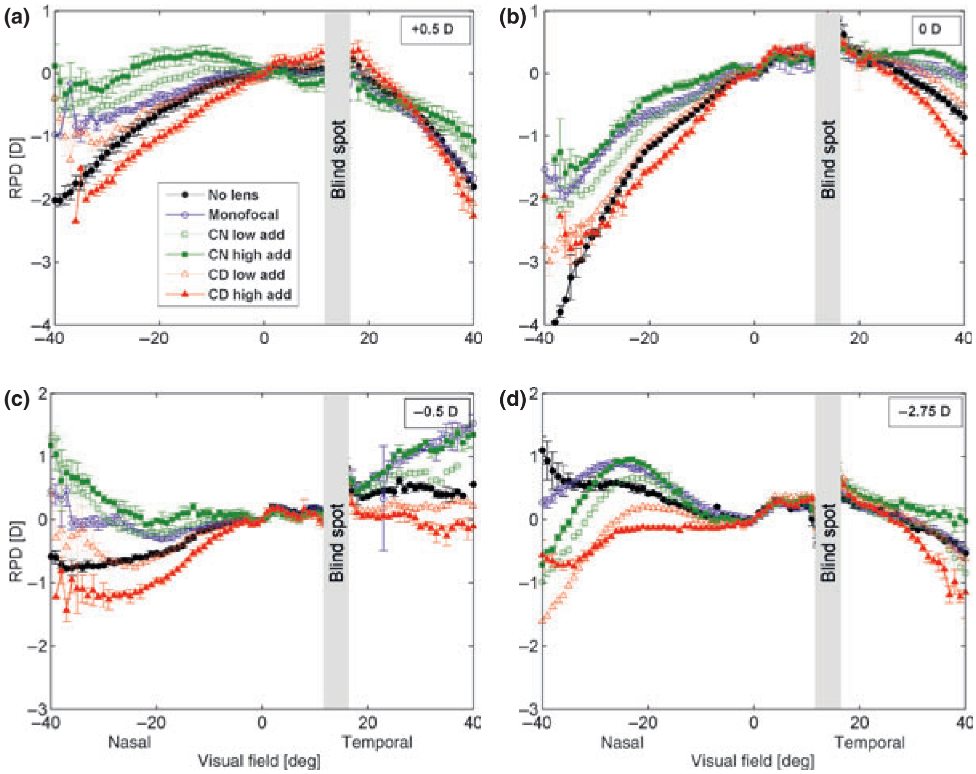

Figure 2. Relative peripheral defocus (RPD) with and without soft contact lenses over the horizontal field of view shown separately for the four subjects (the foveal refraction of each subject is given in the upper right corner of each graph). The RPD presented here is calculated to minimize the RMS error of the wavefront. Angles are given relative to the line of sight. Six different types of correction are shown: without lens (indicated by black filled circles), monofocal contact lens (blue open circles), multifocal contact lens with a low add centre near (CN) design (green open squares), multifocal contact lens with a high add CN design (green filled squares), multifocal contact lens with a low add centre distance (CD) design (red open triangles), and multifocal contact lens with a high add CD design (red filled triangles). The error bars indicate the standard deviation of the four scans made by the wavefront sensor.

Relative peripheral defocus with an image quality metric using the elliptical shape of the pupil

To get a better estimation, defocus was also found by choosing the spherical correction that optimised the area under the MTF curve. Similar to *Figure 2*, *Figure 3* shows the RPD without lens and with the three different lens designs separately for the four subjects, but now calculated from this optimised sphere. As can be seen, the change in RPD with lenses compared to the eye without lens was similar for both metrics. In *Figure 3*, the relative peripheral myopic effect of the centre distance design showed larger fluctuations in optimised defocus over the visual field, reflecting the ambiguity of defining the far point. *Table 2* shows the difference between the mean spherical equivalent obtained by the image quality metric and by minimising the RMS error at various intervals over the visual field with the different lenses. The foveal difference between RMS and optimised defocus was small, but beyond 15° in the nasal visual field and 25° in the temporal visual field, the optimised defocus became more hyperopic both with and without lens, which is why the change in RPD was similar for both metrics.

Peripheral image quality with best spherical correction

When evaluating the higher order RMS wavefront error, a decrease in the peripheral image quality at best spherical correction was found with contact lenses, compared to the naked eye, as can be seen in the upper graph of *Figure 4*. This effect was mainly due to the multifocal design, which gave an increase in the Zernike coefficient for horizontal coma (up to 1 μm larger for a 4 mm pupil at 35° in the nasal visual field). However, as mentioned in *Methods* the RMS error and Zernike coefficients are poor predictors of image quality, particularly in these peripheral measurements through multifocal lenses. To achieve a better estimate of the retinal image quality, we therefore used the same image quality metric

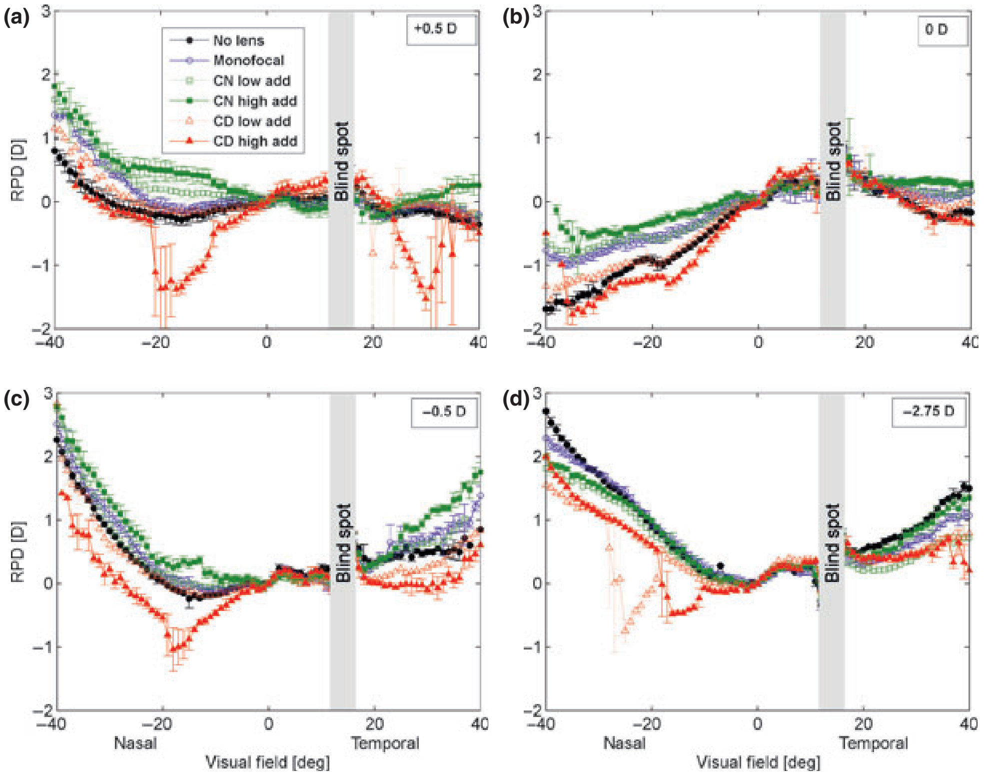

Figure 3. Relative peripheral defocus (RPD) with and without soft contact lenses over the horizontal field of view shown separately for the four subjects (the foveal refraction of each subject is given in the upper right corner of each graph). The RPD presented here is calculated to optimise the area under the MTF-curve. The six different types of correction and the error bars are the same as in Figure 2.

with the area under the MTF curve as described earlier. The lower graph of *Figure 4* shows the change with lenses in area under the MTF averaged for all subjects at optimal defocus. The high add centre distance design decreased the peripheral image quality at optimal defocus, whereas the other lens designs maintained or even increased the quality at best defocus slightly. The increase was due to the negative spherical aberration induced by these lenses, which compensated for the positive spherical aberration of the eye.

Peripheral depth of field

Objective quantification of the magnitude of the depth of field is highly dependent on the chosen metric. Nevertheless, a relative change in depth of field with the different lenses is still of interest, as it is indicative of a real change in depth of field. As described in *Methods*, the depth of field was calculated as the amount of defocus needed to reduce the area under the MTF curve by 20%. Total depth of field was taken as the sum of the negative and positive depth of field. *Figure 5* shows the total depth of field of each contact lens averaged across subjects. Foveally, the depth of field increased slightly with all lenses. On the other hand, in the periphery beyond 10° in the nasal visual field we found a difference between the high add centre distance design and the other designs; the depth of field increased with as much as 0.9 D (at 20° nasally) for the centre distance lens with high add compared to without lens, whereas the other designs maintained or even diminished the depth of field.

Discussion

The Hartmann–Shack wavefront sensor provided reliable measurements of the peripheral aberrations with contact lenses on the eye. Additionally, it was possible to see the presumed border of the optical zone in the raw spot pattern (as shown in *Figure 1*), which is not always possible with the reconstructed wavefront data as, e.g., pupil size or Zernike coefficients. This manual check is an advantage of the Hartmann–Shack technique over other techniques to measure the peripheral refraction through contact lenses, such as Shin-Nippon autorefractors and photorefraction.[29]

The tested contact lenses had an optical zone of around 8.5 mm, which proved to be too small for off-axis angles larger than about 30°, even for the monofocal lens. This

Table 2. Mean difference ± standard deviation in dioptres between the mean spherical equivalent obtained by optimising the area under the MTF and by minimising the RMS error at different angle intervals. A positive difference means that the optimised refraction was more hyperopic than the RMS refraction. The angle intervals are given by the limiting angles (minimum and maximum), separated by a colon, negative angles indicate the nasal visual field

Difference for	−35°:−25°	−25°:−15°	−15°:−5°	−5°:5°	5°:15°	15°:25°	25°:35°
No lens	1.3 ± 0.4	0.5 ± 0.3	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.1	0.1 ± 0.1	0.3 ± 0.4
Monofocal	0.9 ± 0.3	0.2 ± 0.2	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.2	0.3 ± 0.4
Centre near	0.4 ± 0.6	0.1 ± 0.3	−0.1 ± 0.2	−0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.2	0.4 ± 0.5
Centre distance	1.3 ± 0.6	0.4 ± 0.6	−0.1 ± 0.2	0.0 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.5

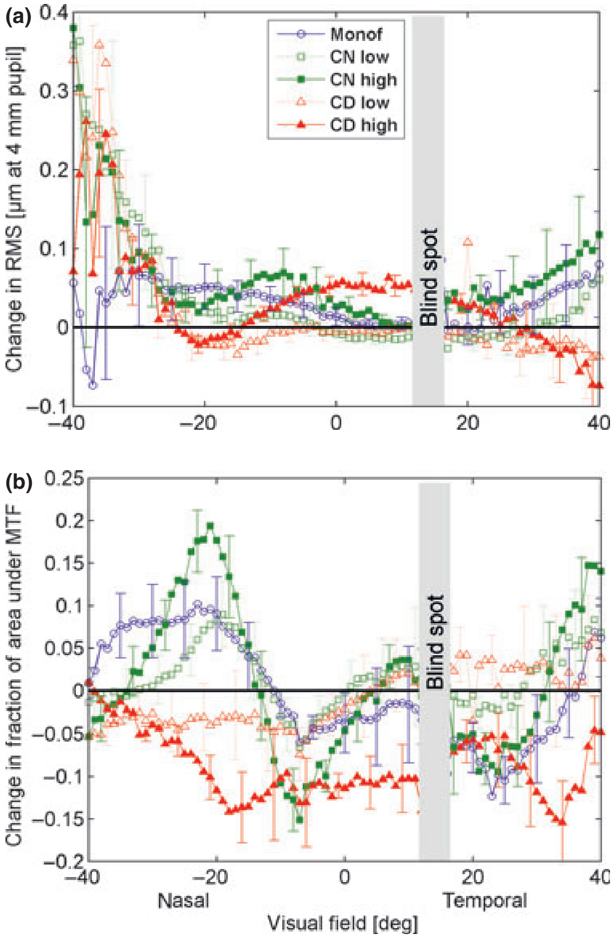

Figure 4. Estimates of the change in peripheral image quality with the different lens designs compared to the uncorrected eye. Upper graph: higher order RMS wavefront error averaged for all subjects. Lower graph: normalised area under MTF out to 10 cycles per degree at optimal defocus compared to the diffraction limited case averaged for all subjects. Five different types of correction are shown: monofocal contact lens (blue open circles), multifocal contact lens with a low add centre near (CN) design (green open squares), multifocal contact lens with a high add CN design (green filled squares), multifocal contact lens with a low add centre distance (CD) design (red open triangles), and multifocal contact lens with a high add CD design (red filled triangles). The error bars indicate the standard error of mean and are plotted for every fifth angle.

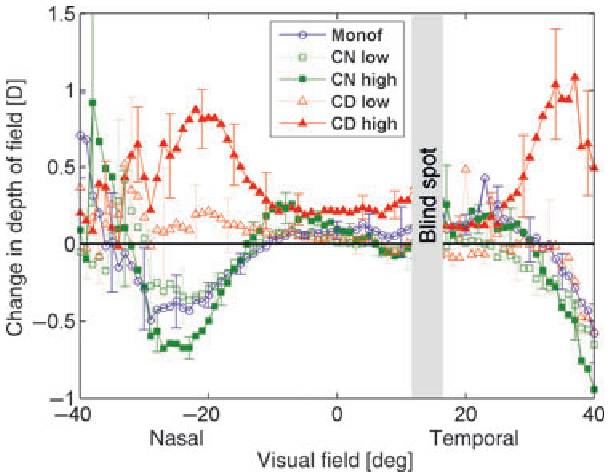

Figure 5. Change in depth of field with the different lens designs compared to the uncorrected eye, given as the full range from the hyperopic to the myopic threshold, averaged for all subjects. The five different types of correction shown are the same as in Figure 4. The error bars indicate the standard error of mean and are plotted for every fifth angle.

limit of about 30° was confirmed by a simple calculation; the contact lens is located approximately 3 mm in front of the entrance pupil of the eye and if we assume that the lens and the pupil are aligned, 30° off-axis means that the projection of the entrance pupil on the contact lens will be shifted by 1.7 mm (3*tan 30°). The projection of a 5 mm entrance pupil will therefore touch the edge of the optical zone for a contact lens with 4.25 mm zone radius (5/2 + 1.7 is 4.2 mm). This together with some displacement of the lens compared to the line of sight could explain why the optical zone edge was visible in our measurements. Since results from animal studies give us no reason to believe that the peripheral control of the emmetropisation process should be limited to the central 60° of the visual field,[1,2] it would probably be an advantage to enlarge the optical zone of the lens. Note that a small optical zone represented not just a technical metrology problem; it also introduced large image degradation in the outer periphery.

Quantifying the refractive error from the reconstructed wavefront is not a simple or unambiguous task. The current study included two metrics: minimising the RMS error and optimising the area under the MTF. Both metrics showed that the multifocal contact lenses with a centre distance design indeed induced peripheral myopia, while a centre near design gave a hyperopic shift in the periphery. For our subjects, the two metrics agreed in RPD in the central part of the visual field but differed in the outer periphery, beyond 15° in the nasal visual field, with the RMS refraction giving a systematically more myopic estimation of the refractive error. Although the refraction given by the two metrics differed substantially in the periphery, this difference was similar both without and with wearing contact lenses, and therefore the change in RPD induced by the lenses estimated by the two metrics was also similar (compare *Figures 2* and *3*).

In the current study on four subjects the low add lens designs had no effect (centre distance lens) or an effect very similar to the monofocal lens (centre near lens). Even with the higher add of 2 D the amount of induced relative peripheral myopia by the lens with centre distance design was small, only around 0.5 D, in agreement with Lopes-Ferreira *et al.*[16] The centre near design had a larger and hyperopic effect on the RPD, as had the monofocal lens because of its negative spherical aberration (note that monofocal *spherical* lenses with negative power have instead been found to have a myopic effect on the RPD[18,30]). Nevertheless, two recent studies found a reduction in myopia progression close to 0.3 D per year using a centre distance design and 2 D add in one multifocal lens and one bifocal lens respectively.[11,12] However, it is not fully understood whether it was the reduction of peripheral hyperopia that caused the reduced myopia progression, or if other factors might have compounded the outcome. In a study that followed myopia progression without any peripheral treatment, Mutti *et al.*[9] found that each dioptre of peripheral hyperopia exacerbated myopia progression with −0.024 D per year. Assuming that this is the case also for lenses, 2 D add only explains one-sixth of the reduced myopia progression in the studies using bifocal or multifocal contact lenses.[11,12] Furthermore, as indicated by our results, the actual influence on peripheral refractive errors is less than the maximal add.

To our knowledge, this study is the first to also assess the peripheral higher order aberrations induced by multifocal contact lenses. We used the traditional RMS error, the area under the MTF, and the objective depth of field to quantify the retinal image quality. The area under the MTF showed that the centre distance design with high add gave a much larger reduction in image quality compared to what was found when only evaluating the RMS error. This reduction in image quality resulted in an increase in peripheral depth of field, at some angles by up to 50%, which can be clearly seen when comparing the results for the centre distance design with high add (red filled triangles) in the lower graph of *Figure 4* with that in *Figure 5*.

Conclusions

The recommendation of this study is to use image quality metrics when analysing the peripheral optical effect of multifocal soft contact lenses, as they provide a more complete description of the change in retinal image quality than the refraction and RMS error calculated directly from the Zernike coefficients. For the four studied subjects we found that the centre distance design with 2 D add gave a minor myopic shift in the periphery out to about 30° off-axis, as the optical zone limit of the lens severely degraded the image quality in larger eccentricities. However, the image quality was also reduced for the near periphery due to the extra aberrations induced by the lens. Actually, the increase in peripheral depth of field with this lens (estimated from wavefront measurements) was of the same order of magnitude as the peripheral myopic shift induced by the centre distance design. If these results hold true also in a larger population, the peripheral myopic shift induced by this lens design is probably too small to explain a possible treatment effect on myopia progression.

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