Optical Quality of Emmetropic and Myopic Eyes in the Periphery Measured with High-Angular Resolution

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Purpose. On average, myopic eyes present a relative hyperopia in the peripheral retina. This has been associated with the possibility that by modifying the peripheral refraction, the progression of central myopia could be controlled. The authors explored how refractive errors and optical aberrations interact in the formation of the retinal image in the periphery, in eyes with different central refractions.

Methods. The authors used a fast and high-angular resolution scanning wavefront sensor to measure the optical image quality of the eye in the horizontal meridian (± 40°) in 202 eyes of 101 subjects, 54 males and 47 females with an average age (std) of 27.5 (± 7.2) years and an average foveal refraction (std) of −0.8 (± 1.3 D) of which 64 were non-myopes (refraction ± std: 0.01 ± 0.46 D) and 37 myopes (−2.12 ± 1.08 D). They evaluated the relationship between peripheral optical properties and central refraction using different metrics.

Results. The authors observed a significant tendency to a relative hyperopia in the periphery of the myopic eyes. The relative peripheral refraction (RPR) was significantly different between the emmetropic and myopic eyes from 15°–40° temporal retina and from 20°–40° nasal retina. The mean RPR metric correlated with the central refraction of the subject ($r = -0.552$ / -0.560 [OD / OS]). The image quality presented only minor differences between the various refractive groups at angles of 30°–40° when the central refraction was corrected.

Conclusions. Peripheral overall blur is mostly influenced by the interaction of defocus and oblique astigmatism, and at larger eccentricities is similar for the different refractive groups. This could argue against the hypothesis that a relative peripheral hyperopia could drive eyes toward myopia. (*Invest Ophthalmol Vis Sci.* 2012;53:3405–3413) DOI:10.1167/iovs.11-8993

Various studies have investigated the optical quality of the human eye in the periphery considering not only refractive errors.[1–3] One interest is to better understand the relationship between peripheral optics and spatial vision performance.[4–7] In addition, the hypothesis that peripheral refraction may have an impact on myopia development[8–10] made it even more interesting to explore the optical properties of the eye at peripheral angles. In this line of research, most previous efforts concentrated on measuring peripheral refractive errors, usually at a relative small number of eccentricities.[11,12] However, in a complex optical system as the eye, it is not sufficient to consider only the spherical refractive error (defocus) to predict the amount of blur in the retinal image. It would be better to consider the overall image quality, which is the result of the interaction of refractive errors and higher order aberrations. Moreover, the low-angular resolution of the data collected in most previous studies did not show the complete description of the variation of the optical properties with eccentricity.

A common practice for measuring peripheral refraction is the use of a modified existing commercial instrument designed for central refraction, or aberration, measurements.[13] These modifications often involve keeping the instrument at a fixed location, while asking the subject to look at the desired fixation points throughout the visual field. Several drawbacks occur when measuring peripheral optics in this way. It is possible that the eye's optics changes between the measured angles due to eye movements or changes in fixation. Because of the time-consuming sequenced measuring method, low-angular sampling density is often chosen to minimize the acquisition time. Although moving the eye was found not to have a significant impact,[14,15] longer experimental time and the low-angular resolution will reduce the reliability of the data, since ideally the eye should be compared at each eccentricity in the same state. To overcome these problems, the authors developed a scanning sensor for measuring the eye's peripheral optics.[16] This instrument is based on the Hartmann–Shack (HS) wavefront sensor, but its potential lays in the rotational movement reaching high speed acquisition with high accuracy over a large range of field angles (80°). This system provides complete wavefront aberration data with an angular resolution of 1°. There are several advantages of collecting peripheral optical data in the eye at a high-angular resolution. First, erroneous or not representative measurements can be readily detected. A non-representative data point is a measurement that falls outside the normal, continuous shape of the recorded curve at a specific retinal location. This could be real due to a small hole or bump on the retina, or to some optical effect, but more likely it is caused by some artifact in the measurements. If such data is one of the few points when sampling at low density, a wrong interpretation of the measured information could appear. A second benefit concerns shape fitting. More data points result in a more accurate representation of the real shape. Especially when fitting higher order polynomials, more data points are required. This would allow for the detection of micro-variations in the quality of the peripheral optics. While low-angular data could insinuate that two eyes have similar relative peripheral optics, high-angular resolution data could reveal significant smaller scale differences.

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In this study, the authors used the scanning HS sensor to measure the first high-resolution wavefront data over 80° of the visual field in a relatively large population of emmetropic and myopic young subjects. The high-angular resolution aberration data was analyzed to better understand the peripheral optics in the human eye. The optical quality of the retinal images in the periphery was analyzed as a function of the central refraction. Different optical quality metrics were calculated as a function of eccentricity for the population. These metrics were used to determine the combined impact of high order aberrations and refractive errors as a function of eccentricity.

METHODS

Subjects and Data Collection

Measurements were done using a fast scanning peripheral HS wavefront sensor. The central 80° of the visual field along the horizontal meridian were sampled at 1° intervals in four consecutive scans. The total acquisition time was 7.2 seconds. Detailed information of the instrument has been described elsewhere.[16] In summary, after the eye is illuminated with an infrared beam (780 nm), the outcoming wavefront is sampled by an array of microlenses, placed optically conjugated with the pupil plane of the subject's eye, to reconstruct its aberrations,[17] as an expansion of Zernike polynomials. The data of all four scans were checked before post-processing. If anomalies occurred in one of the scans, it was discarded before averaging. If two or more scans were not correct, the measurement was not used.

The subject was placed in a chinrest looking at a red dot created by a laser pointer on a cardboard at 2 m from the subject. All the measurements were collected under normal viewing conditions, without cycloplegia. While the operator was aligning the system, the subject maintained normal blinking. The system was aligned to the visual axis of the subject. To avoid corneal reflections in the HS-images, the illumination beam was aligned to enter the eye slightly below the center of the pupil. Once the system was initialized, the subject was asked to blink before starting the measurements.

To deal with the elliptic pupil shape of the off-axis measurements, Zernike coefficients are first calculated for a unit circle encircling all connected HS-spots, and then mathematically rescaled to a fixed elaboration pupil diameter.[18] The unwrapped HS-image was only further processed when the minor diameter of the fitted ellipse around all connected HS-spots was larger than 90% of the elaboration diameter of 4 mm; otherwise, it was discarded. This ensures that the result no longer is influenced by the initially extrapolated part of the wavefront. All aberration data described are for 780 nm wavelength light. No chromatic recalculation was done to avoid the possible effect of the small variation in chromatic aberrations found with eccentricity.[19]

Both eyes of 101 Caucasian subjects (54 males and 47 females) were measured. Subjects (between 15 and 49 years: mean [std] age 27.5 [± 7.2] years) with eyes without ocular pathologies or post-operative were selected. Their central refractions were within the dynamic range of the instrument (mean foveal refraction [std] OD / OS: −0.77 [± 1.25 D] / −0.81 [± 1.31 D], ranging between −4.6 and +3.2 D), and therefore they were measured without any ophthalmic correction. The separation in refractive groups was based on the measured central mean spherical equivalent (Mc) and is shown in Table 1. When comparing emmetropes (EMM) ($Mc \geq -0.75$ D) to myopes (MYOP) ($Mc < -0.75$), 37 EMM were randomly chosen of the 63 (one hyperopic subject with a refraction larger than 1 D was eliminated for analysis) to match the MYOP quantity for statistical reasons.

The use of the sensor and the complete experiment followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all subjects after they were fully informed about the nature and the possible consequence of the measurements.

TABLE 1. Division into Refractive Groups (GRx, with x = 1 to 6)

M_c (#)	> 0.51 (GR1)	0.5 / −0.49 (GR2)	−0.5 / −1.49 (GR3)	−1.5 / −2.49 (GR4)	−2.5 / −3.49 (GR5)	< −3.5 (GR6)	*EMM ($M_c \geq -0.75$)*	*MYOP ($M_c < -0.75$)*
OD	1.15 ± 1.16 (5)	−0.03 ± 0.26 (52)	−0.95 ± 0.31 (20)	−1.98 ± 0.34 (13)	−3.17 ± 0.37 (6)	−3.70 ± 0.27 (5)	*~ 0 ± 0.5 (rand. 37)*	*−2.09 ± 1.00 (37)*
OS	0.63 ± 0.13 (7)	0.02 ± 0.25 (48)	−0.95 ± 0.34 (23)	−2.02 ± 0.29 (10)	−2.80 ± 0.32 (6)	−4.12 ± 0.33 (7)	*~ 0 ± 0.5 (rand. 37)*	*−2.21 ± 1.15 (37)*

The first row gives the boundary values of the different groups. The second and the third row give, respectively, for OD and OS the central refraction (Mc) (mean ± std) and number of subjects (#) of each specific group. The two columns with data in italics present the information for the division into two single groups of emmetropic and myopic subjects.

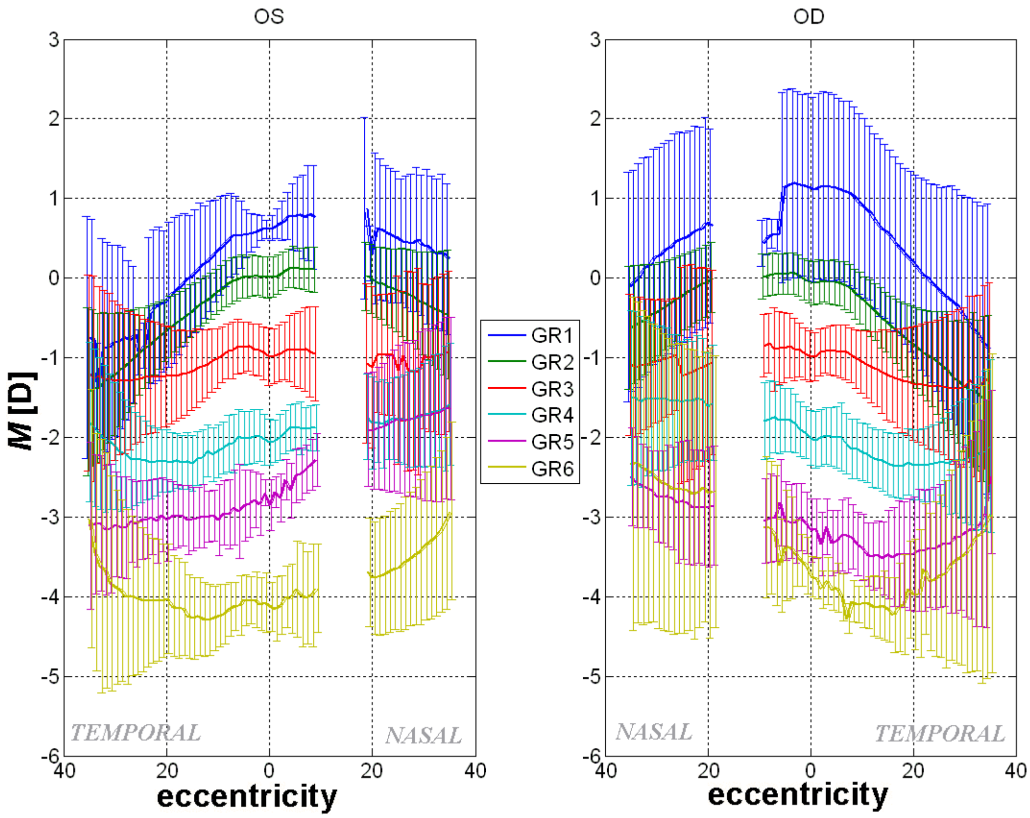

FIGURE 1. Average and standard deviation of M [D] for each refractive group GRx, with GR1 being the most hyperopic. Toward the periphery, the mean values of the different groups bend toward a similar point but the standard deviation also grows, representing large variations within the same refractive groups.

Data Analysis and Metrics

The mean spherical equivalent (Mc) calculated from the second order Zernike coefficient (C_2^0) was used to quantify the central refraction of the subjects (the mean of the central 5°). By using Mc, the population was examined in three ways: i) considering the whole population using Mc as a continuous variable; ii) bundling the subjects with similar central refraction (division in refractive groups (GRx) with the boundaries given in Table 1); and iii) dividing the population into two groups of emmetropes and myopes (EMM/MYOP). The mean and standard deviation of the relative peripheral refraction (RPR) and the horizontal astigmatic term (J0) were examined. Both were determined in diopters using the second order Zernike coefficients C_2^0 and C_2^2 respectively. In addition, horizontal coma (Coma_H) was evaluated (C_3^1 [μm] for a 4 mm pupil). Shape metrics were defined to quantify the variation of the mean spherical equivalent (M) and J0 as function of eccentricity. The first metric was the mean relative peripheral refraction (M RPR), which is the integration of the RPR over the scanned visual field, excluding the area around the optic disk (10° to 18° of the nasal retinal side). A negative value implies relative more myopic refraction, compared to Mc. The other shape metric was the quadratic coefficient of the second order fit to horizontal astigmatism, J0 as a function of eccentricity. A small value indicates small variation between the central and peripheral J0. The metrics were statistically examined using unpaired *t*-tests or ANOVA tests when the variables were independent. The data of both eyes were examined separately.

The impact of eccentricity on the overall blur of the retinal image was investigated by calculating the point-spread function (PSF) from the measured aberrations for each subject and eccentricity. This was done for the standardized 4 mm pupil diameter, taking into account the variation of the off-axis pupil shape (off-axis horizontal diameter of the pupil aperture was multiplied by cos[eccentricity]). The Strehl ratio, the quotient between the maximum intensity in the measured PSF as compared with that in a diffraction-limited system, was used to quantify the image quality. Three different situations were tested: i) uncorrected (ST1); ii) correcting the central refractive errors ($C_2^{-2/0/2}(ecc)' = C_2^{-2/0/2}(ecc) - C_2^{-2/0/2}(fovea)$) (ST2); and iii) correcting the refractive errors ($C_2^{-2/0/2}(ecc)' = 0$) at each angle (ST3). To visualize the degradation induced by the optics of the eye at different eccentricities, the retinal image of an object (letter E: size 30′ arc) was estimated by convolving the object with the PSF of the different conditions. ANOVA tests were used to examine the difference between the various groups (refractive groups and EMM/MYOP) for all three situations.

As a final analysis, the results of both eyes for each subject (OD / OS) were compared using a repeated measures (RM) ANOVA test. In general, the applied statistical test is always mentioned explicitly when *P* values are cited. In several subjects the outermost eccentricities (angles > 35°) showed severe distorted HS-spot patterns at one side of the image. Those angles and the eccentricities affected by the optic disc (10° to 18° at the nasal retinal side) were discarded from the analysis.

RESULTS

Peripheral Refraction and Shape Metrics

By definition, the mean spherical equivalent (M) is centrally different between the refractive groups. But also at all angles, significant differences ($P < 0.05$) between the different groups were found using an ANOVA test. Figure 1 shows the means and standard deviation of the results. The groups are organized in order of refraction with GR1 being the most hyperopic group (see Table 1). Other coefficients with significant difference between the refractive groups over a large angular range were J0 (horizontal astigmatic term) at the temporal retina and horizontal coma (Coma_H) at the nasal retina. The mean relative peripheral refraction (M RPR) between the different refractive groups was significantly different ($P <$ 0.001) for both eyes using an ANOVA test. In general, significant difference was observed between the first two refractive groups and the last four (except for OD combination GR1/GR3 with $P = 0.053$ and OS combination GR1/GR3 with $P = 0.183$). The transition from refractive group 2 to 3 coincides with the transition from emmetropic to myopic eyes. For that reason, significant difference ($P < 0.001$) in M RPR between the emmetropic (EMM) and myopic (MYOP) groups (see Table 1) was found also (OD: EMM/MYOP −0.474 ± 0.359/+0.021 ± 0.507; OS: −0.404 ± 0.329/+0.076 ± 0.436). Finally, the M RPR-metric and Mc correlated significantly. The Pearson correlation coefficients were −0.552 and −0.560 for OD and OS, respectively. The correlation plot is shown in Figure 2. The regression line fitted through all data points (OD and OS) had a slope of −0.19 and an offset of −0.39.

The shape factor aQ-J0 (see Methods) was found to be significantly different between the refractive groups when using an ANOVA test (*P* value: 0.002/0.018 for OD/OS), but the Tukey post-hoc analysis did not confirm a dominant trend. When dividing in EMM and MYOP groups, aQ-J0 was significantly different between the two ($P < 0.001$), with mean and standard deviation values (EMM/MYOP) −0.0011 ± 0.0003/−0.0009 ± 0.0003 for both right and left eyes. The Pearson correlation coefficient between aQ-J0 and Mc was −0.374/−0.254 (OD/OS) indicating that only a small percentage (14%/7%) of aQ-J0 can be explained by the central refraction (Mc). This result can be translated to less relative oblique astigmatism for the average myopic subject compared to the average emmetropic subject. The rate of decrease at 40° of eccentricity is approximately −0.25 D per 2 D of Mc.

An unpaired *t*-test was used to investigate the difference between the EMM and MYOP groups at each angle for both eyes separately. The results are presented in Figure 3. Significant differences were found for relative peripheral refraction at the temporal retina from 15° onwards and at the nasal retina from 20° onwards. The MYOP group had significantly less relative myopia in this region compared to the EMM group. The normalized J0 coefficient was significantly different in the temporal retina from 8° onwards, showing a larger J0-variation between the foveal and eccentric locations for the EMM group compared to the MYOP group. Further horizontal coma (Coma_H) was significantly different in the nasal retina from 4° onwards. The absolute value of the mean-curve of the myopic group was larger than that of the emmetropic group, representing larger amounts of coma at the nasal retina.

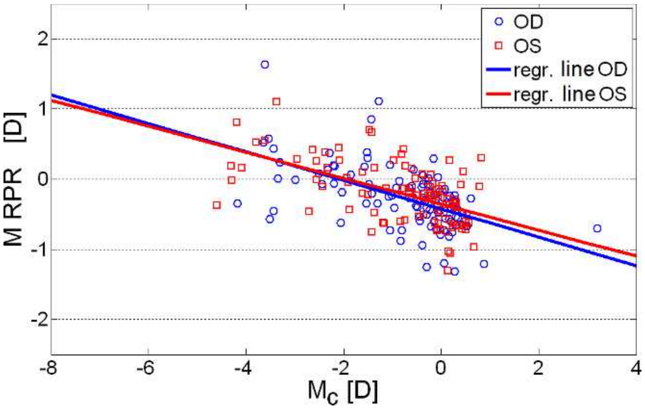

Figure 2. Correlation plot between Mc and M RPR for OD and OS with their regression line.

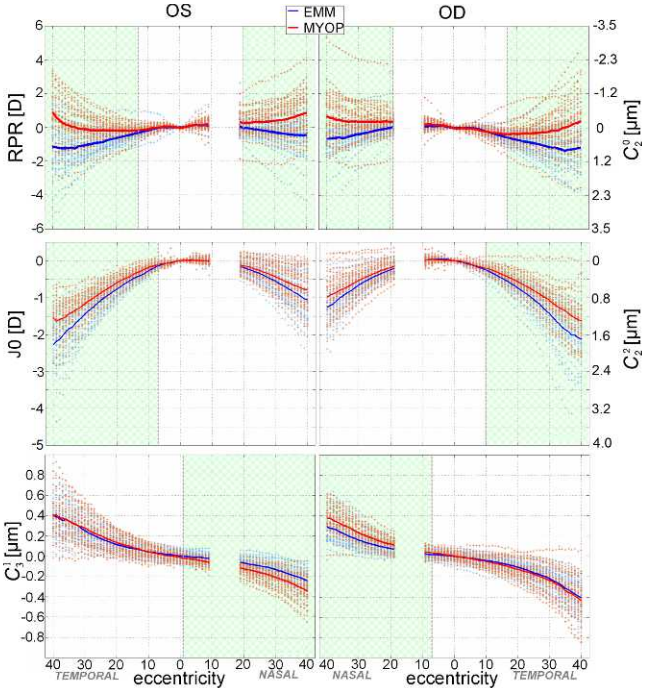

Figure 3. Comparison between the EMM (*blue*) and MYOP (*red*) for OD (*right*) and OS (*left*), taking into account the eye's symmetry. The dimensions of the x-axis are degrees of visual angle. Respectively, the (*top*) RPR, (*middle*) J0, and (*bottom*) Coma_H data plots are shown, calculated from a 4 mm pupil. The area marked in *green* is the area in which the mean values between EMM and MYOP group were significantly different. For the RPR and C0, the values of the corresponding Zernike coefficient [μm] are indicated on the right side of the figure for comparison of the magnitude with Coma_H.

The Zernike coefficients of the second to the fourth order (4 mm pupil) of OD and OS were compared using paired *t*-statistics. The Pearson correlation coefficient (*r*), the significance of correlation (*p*), the slope of the linear regression curve (slope) and the coefficient of determination (*r*2) are given in Table 2 for the foveal vision (eccentricity equal to 0°) and for the whole investigated visual field (central 70° of the visual field except for the area of the optical nerve: 10° to 18° nasal retina). The same nasal and temporal angles of each subject were compared. Negative correlation was found for the Zernike modes with odd powers of the X-coordinate, as reported earlier for the central[20] and the peripheral retina.[21] The *P* value in Table 2 indicates whether the correlation coefficient was significant different from 0, but from a symmetry point of view, the slope of the regression curve should be close to 1 (or −1 in case of inverse symmetry). On-axis this was almost the case for the second (slope = 0.964) and fourth (slope = 0.942) order defocus Zernike modes, and for the whole range in addition to the second order defocus (slope = 0.941), the horizontal astigmatic term (slope = 0.909) and the horizontal coma term (slope = −0.937) had a close to unit relation due to their strong dependency on the angle of eccentricity.

Peripheral Retinal Image Quality

Figure 4 presents the values of the Strehl ratio of the right eyes as a function of eccentricity for the different conditions (see Methods). On-axis defocus had the largest impact on the degradation of the retinal image (Fig. 4: ST1). Figure 3 shows

Table 2. Overview of the Comparison of OD and OS on-Axis (0°) and for the Whole Measured Angular Field (−35° to 35°)

	0°				−35°/35°			
C(n,m)	***r***	***p***	**slope**	***r*2**	***r***	***p***	**slope**	***r*2**
(2,−2)	−0.469	0.000	−0.525	0.220	−0.604	0.000	−0.678	0.365
(2,0)	0.924	0.000	0.964	0.854	0.918	0.000	0.941	0.843
(2,2)	0.798	0.000	0.846	0.637	0.885	0.000	0.909	0.783
(3,−3)	0.665	0.000	0.749	0.442	0.619	0.000	0.720	0.383
(3,−1)	0.671	0.000	0.763	0.450	0.649	0.000	0.710	0.421
(3,1)	−0.529	0.000	−0.556	0.280	−0.926	0.000	−0.937	0.857
(3,3)	−0.477	0.000	−0.372	0.228	−0.662	0.000	−0.552	0.438
(4,−4)	−0.246	0.013	−0.212	0.061	−0.283	0.000	−0.288	0.080
(4,−2)	−0.137	0.171	−0.156	0.019	−0.459	0.000	−0.492	0.211
(4,0)	0.893	0.000	0.942	0.797	0.771	0.000	0.800	0.594
(4,2)	0.626	0.000	0.707	0.392	0.542	0.000	0.527	0.294
(4,4)	0.622	0.000	0.635	0.387	0.293	0.000	0.248	0.086
#	101				6288			

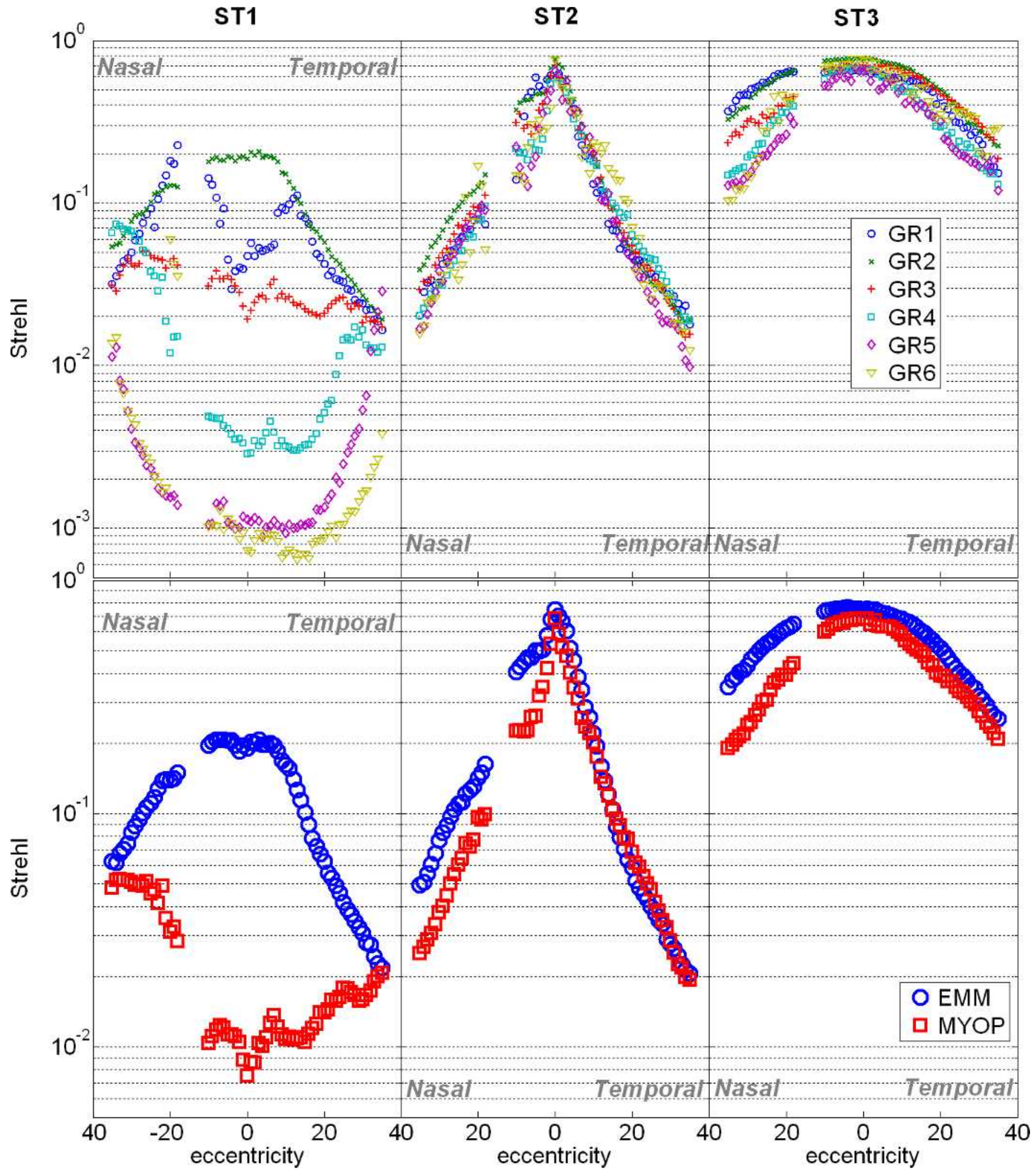

Figure 4. Variation of the Strehl ratio (only OD) for three different situations: uncorrected eye (*left panel*), correction of central refraction (*central panel*), and angle specific correction of refraction (*right panel*). It is shown for the comparison between the refractive groups (*upper row*) and the EMM/MYOP groups (*bottom row*).

that oblique astigmatism is the aberration term that varies the most as a function of eccentricity (for easy comparison the scale of the Zernike coefficient expressed for a 4 mm pupil [μm] is added to the graph). Therefore, it will have a dominant impact on the image quality in the periphery. On average, it degraded the retinal image for the hyperopic and emmetropic subjects, while in contrast it removed some peripheral retinal blur of the average uncorrected myopic subject (Fig. 4: ST1). This type of compensatory behavior resulted in a similar image quality between the different refractive groups at larger eccentricities. Correcting central refraction (Fig. 4: ST2) showed the marked dominancy of oblique astigmatism in the periphery. Nevertheless, the ANOVA test found the means of all refractive groups significantly different, though the Tukey post-hoc test showed that only refractive group 2 (GR2), which contains the subjects with the "best" vision, was significantly different from the others, while no other clear trends were observed. Correcting each angle-specific refractive error (Fig. 4: ST3) showed a variation between the refractive groups and the EMM/MYOP at the nasal retina, although the observed variation between the different groups on the absolute blur is small. The values of the Strehl ratio over the whole angular field under condition 3 (ST3: GRx) were almost similar to that of the central retina of an average emmetropic subject (ST1: GR2).

Figure 5 shows both the retinal images of a point source (point-spread functions; PSFs) (A) and the retinal images of a letter "E" (size 30′ arc) (B) for a representative emmetropic and a myopic subject as a function of eccentricity. The three cases are represented: no refraction corrected (ST1), central refraction corrected (ST2), and refraction corrected at each eccentricity (ST3).

DISCUSSION

Peripheral Refraction and Aberrations: Comparison with Previous Studies

The authors presented the results of high-angular resolution peripheral optical image quality measured in a population. They found that the relative peripheral refraction was significantly different between emmetropic and myopic subjects at the temporal retina from 15° and the nasal retina from 20°. Its shape varied as a function of the subjects' central refraction. Also, significant differences were observed for horizontal astigmatism (from 8° temporal retina) and for horizontal coma (from 4° nasal retina). The interaction between defocus and oblique astigmatism was the main contributor to the overall peripheral blur.

In Atchison et al.,[22] refraction was measured along the horizontal meridian with a Shin-Nippon SRW5000 auto-refractometer (Shin-Nippon Commerce Inc., Tokyo, Japan) in steps of 5° out to 35° for subjects turning their eyes. The results were fitted with a second order polynomial after subdividing their population in refractive groups. They found the sign of the second order coefficient to change from negative to positive between -1 and -2 D. In the present study's data, the turnover point, where relative peripheral myopia changed to relative hyperopia, was found to be around 2 D of myopia, which is in good agreement with that study. Another observation in Atchison et al. is that the variation between the refractive groups was stronger at the temporal retina (significant from 5° onwards) than at the nasal retina (significant from 20°–25° onwards), which coincides with the authors' findings of the comparison of the RPR between the EMM and MYOP population, where significant differences were found for the temporal retina already from 15° while at nasal retina from 20°. However, Mathur et al.[23] did not find a systematic trend toward a more hyperopic RPR with increasing axial myopia. In the present study, the authors found a significant correlation between M RPR and the refractive group, although large variability between individuals of the same refractive group were observed, as is shown by the error bars in Figure 1 and the spread in Figure 3. The difference between the findings could be due to the size of the population or because they only measured up to ±21° of eccentricity. As already mentioned, large variation for subjects of the same refractive group was found for each of the discussed metrics. This observation could suggest that the relative peripheral refraction may not be the dominant factor that drives eyes to become myopic, rather than only another variable in the myopia development process. Similarly, as in many previous studies, the authors also found a strong reduction in the amount of the aberrations with increase in the order. The second and third order RMS showed a strong variation with eccentricity, and the values were higher for the temporal retina compared to nasal part. One especially interesting high-order aberration term was coma. The linearity of coma with eccentricity as described in earlier studies[24–26] was not observed in the present study's data. A linear curve was only the best fit for the central 40°, while for larger ranges of field angles a third order polynomial was a significantly better choice. Low-angular resolution and the method used to calculate the peripheral wavefront are believed to be the cause of this discrepancy. The impact of the method was confirmed by recalculating the wavefront after first stretching the horizontal coordinate with a cosine-correction to compensate for the vignetting of the eye's pupil when measuring obliquely. A linear change of horizontal coma with eccentricity was then obtained.

Peripheral Retinal Image Quality

Beyond considering independently higher order aberrations and refraction metrics, the authors calculated the actual effect of the complete eye's optics on the retinal image quality taking into account the variation of the pupil shape with eccentricity. The PSF and simulated retinal images of a letter "E" were calculated for the different situations at each eccentricity. This allowed them to quantify the relative impact of the refractive errors and aberrations to the overall retinal blur. The authors used the Strehl ratio as a retinal image quality metric. Their results clearly showed that refractive errors are the main contributors of retinal blur both on- and off-axis. Correcting only the central refractive errors is not sufficient to ensure a high-quality peripheral image, due to the strong increase of astigmatism with eccentricity. In this situation, the nasal retina was found to be the area where the largest difference occurred between emmetropic and myopic subjects. When central refraction is corrected, peripheral blur is mostly produced by oblique astigmatism, but the magnitude is similar for all refractive groups. This argues against the hypothesis that peripheral blur might be a trigger that drives the eye toward myopia. It is even enforced by the finding that the image quality for both emmetropic and myopic eyes is very similar around 30°–40° of eccentricity. However, these measurements were obtained in adults with stable refractions. It is therefore hard to predict whether the measured situation is the end phase after correcting possible differences. Further, only the overall retinal blur was considered. For the considered 4 mm pupil diameter, the impact of higher order aberrations was observed to be only of minor importance. Although a significant difference of the Strehl ratio at the NR between emmetropes and myopes was found, the real impact on image degradation was small. The blur due to the higher order aberrations will increase when larger pupils are considered, although no major deviations from the current observations are expected.

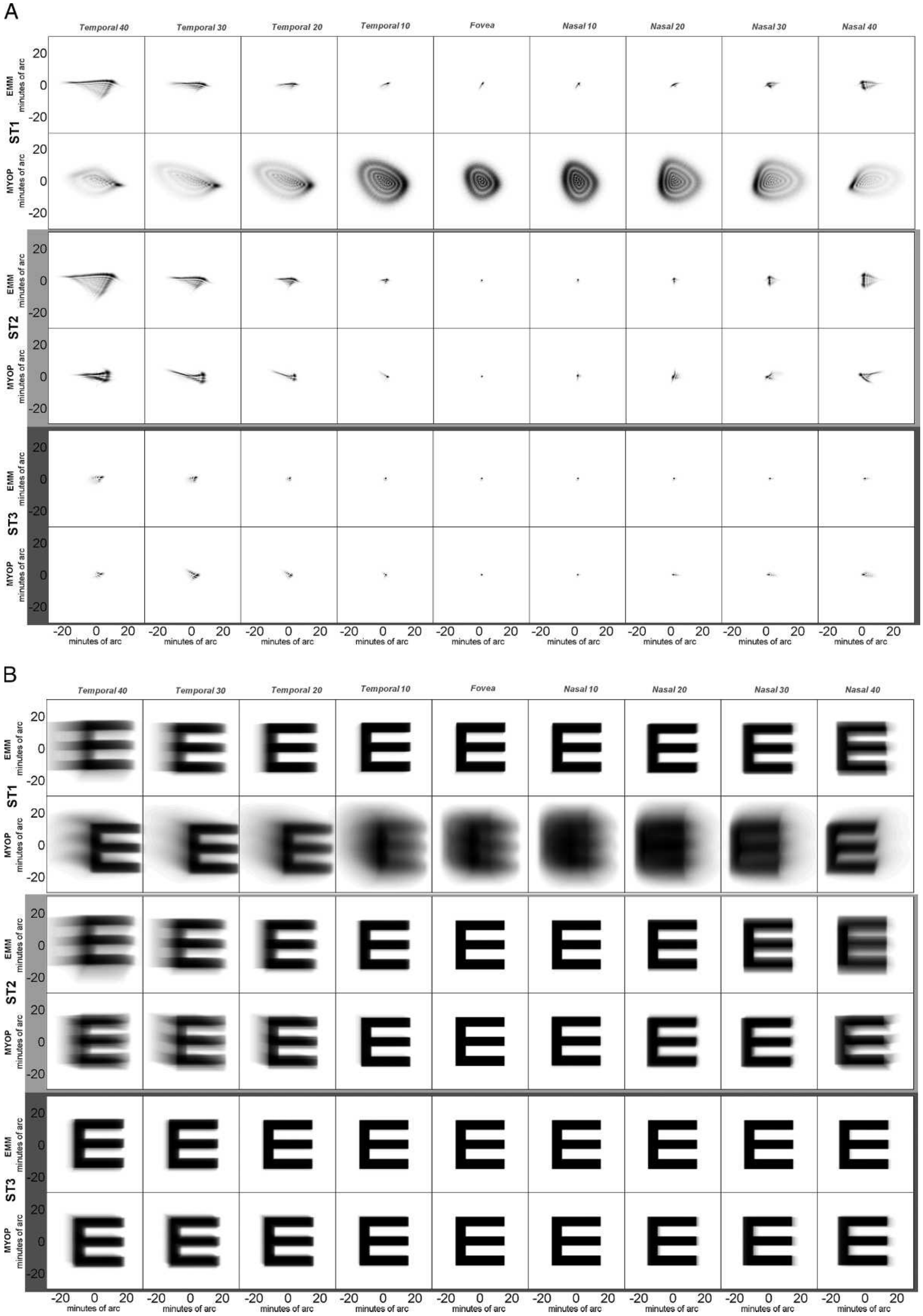

FIGURE 5. Simulation of retinal image (**A**) PSF, and (**B**) convolution with letter E (size 30′ arc) of a representative emmetropic (*odd rows*) and myopic (*even rows*) eye at 9 different eccentricities (left to right: temporal to nasal retina). The three sets of images are from top to bottom ST1, ST2, and ST3, respectively.

It might be argued that the authors could have used alternative image quality metrics. However, it is recognized[27,28] that most of them, when calculated on the retinal plane, provide a similar and accurate prediction of blur. The discussed results are for monochromatic light. Nevertheless, in daily life we are exposed to polychromatic light. If only small differences in image quality are found between the various refractive groups when examining with monochromatic light, it is not hard to imagine that those might be further masked when the full wavelength spectrum is investigated. Although significant differences in image quality could be detected using this sensitive instrumentation, these are probably within the range of normal variability.[29,30] For example, the authors found significant difference in the image quality between EMM and MYOP subjects at the nasal retinal side after correcting the refractive errors at each angle; however, the impact of this difference was smaller than the average variability for central vision in emmetropic eyes (mean ± std: 0.17 ± 0.15, ranging between 0.02 and 0.89), and therefore it is considered to have a marginal impact on the development of myopia.

Implications for Optical Control of Myopia Development

The results of this study may have some implications in the context of the current efforts to control myopia development by modifying the refraction in the periphery. These approaches are based on the well-established result that myopes tend to be relatively more hyperopic in the periphery. Then, spectacles or contact lenses that render the peripheral retina relatively more myopic would help to reduce the relative blur and eventually neutralize the retinal signals promoting eye growth. Although some studies showed that a relative peripheral hyperopia may precede myopia,[31,32] others were not able to find a relationship between peripheral refraction and the subsequent onset of myopia.[33,34] If a significant relationship is actually confirmed, the practical implications for the optical control of the peripheral refraction would be enormous. The authors found here that peripheral blur, when central relative defocus is corrected, is mainly produced by oblique astigmatism and moreover, it is similar for both myopes and emmetropes. Even more apparently surprising was the observation that, due to the coupling of defocus and oblique astigmatism, the peripheral blur of the average uncorrected myopic subject was similar to that of the average emmetropic subject at 30°–40° of eccentricity. This implies that when, for example an addition of 2 D in the periphery is applied as target to compensate peripheral hyperopia, it would not reduce peripheral blur in most cases. It would even be possible that in some particular conditions, the correcting elements would increase retinal blur. If the emmetropization mechanism is driven by relative blur in the periphery, the authors would have expected to find significant differences in the overall blur between myopic and emmetropic eyes. But this was not the case in the present study.

The situation is however quite complex with many different interactions. For example, it was shown[35] that chick eyes ignore a cross cylinder of −5/+5D but respond to a small spherical refractive error on top of the large astigmatism. In the authors' calculations, they presented an overall blur without considering nasal/temporal asymmetries. On the other hand, to achieve a substantial reduction of blur, strategies correcting oblique astigmatism should be devised, beyond simple approaches, purely based on the addition of some amounts of peripheral defocus.

It should be mentioned that the authors' results were obtained in adults with relatively low amounts of stable myopia. This makes it hard to decide whether the peripheral refractive errors and blur were a consequence or a cause of central refractive development. Although there may be interactions between peripheral and foveal refractive development, when they are considered together, the causes and the consequences of refractive changes cannot be separated. The results of this study illustrated the high complexity of the optical properties of the eye in the periphery when trying to understand their contribution to myopia development. But future studies of the peripheral optical quality in high myopes and/or children with progressing myopia will be necessary to determine the actual importance of peripheral optics.

CONCLUSIONS

The authors measured with high-angular resolution the peripheral optical quality in eyes of a relatively large population using an instrument especially designed and developed for this purpose. The superiority of a peripheral scanner for doing population studies examining peripheral optical quality was confirmed.

Retinal image quality metrics provided good insight to the relative blur across the peripheral retina. Off-axis astigmatism was found to be the main contributor to peripheral image degradation in every normal eye regardless of its central refraction. Also, a compensatory behavior between defocus and oblique astigmatism was observed, resulting in a similar image quality between the different refractive groups at the larger eccentricities (30°–40°). This may question the hypothesis that modifying the peripheral optics could prevent myopia progression. There are some implications for the suggested approaches to control myopia development by correcting peripheral refraction. For example, a correction of 2 D of defocus in the periphery would not improve the retinal image significantly, and it is even plausible that in some cases it would be worse due to some aberration coupling. It is advisable to consider retinal image quality metrics when investigating the hypothesis that a relative peripheral hyperopia could drive eyes toward myopia, or when evaluating optical strategies to stabilize myopia progression.

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