Minimum amount of astigmatism that should be corrected

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PURPOSE: To evaluate how small amounts of astigmatism affect visual acuity and the minimum astigmatism values that should be corrected to achieve maximum visual performance.

SETTING: Optics Laboratory, University of Murcia, Murcia, Spain.

DESIGN: Case series.

METHODS: A wavefront sensor was used to measure astigmatism and higher-order aberrations (HOAs) in normal young eyes with astigmatism ranging from 0.0 to 0.5 diopter (D). Astigmatism was corrected for natural pupil diameters using a purpose-designed cross-cylinder device. Visual acuity was measured for high-contrast and low-contrast stimuli at best subjective focus with the natural and corrected astigmatism. From the aberrations, optical image-quality metrics were calculated for 3 conditions: natural astigmatism, corrected astigmatism, and astigmatism only (with all HOAs removed).

RESULTS: The study evaluated 54 eyes. There was no significant correlation between the amount of astigmatism and visual acuity. The correction of astigmatism improved visual acuity for only high-contrast letters from 0.3 D, but with a high variability between subjects. Low-contrast visual acuity changed randomly as astigmatism was corrected. The correction of astigmatism increased the mean image-quality values; however, there was no significant correlation with visual performance. The deterioration in image quality given by astigmatism higher than 0.3 D was limited by HOAs.

CONCLUSIONS: In most subjects, astigmatism less than 0.5 D did not degrade visual acuity. This suggests that under clinical conditions, the visual benefit of precise correction of astigmatism less than 0.5 D would be limited.

Financial Disclosure: No author has a financial or proprietary interest in any material or method mentioned.

J Cataract Refract Surg 2014; 40:13–19 © 2013 ASCRS and ESCRS

Human vision is limited by the optical quality of the eye, especially by the presence of refractive errors (ie, defocus and astigmatism). Although the eye is also affected by higher-order aberrations (HOAs) such as trefoil, coma, and spherical aberration, in normal eyes these aberrations have a small impact on high-contrast visual acuity (HCVA).[1] However, in most persons with healthy eyes, uncorrected defocus and/or astigmatism significantly deteriorates the quality of vision. Spectacles typically correct both defocus and astigmatism with an accuracy of 0.25 diopter (D). With toric contact lenses, the lack of rotational stability reduces the efficacy of astigmatism correction.[2,3] As a consequence, many companies manufacture only contact lenses with cylindrical powers of 0.75 D or higher in steps of 0.50 D. On the other hand, despite recent advances in laser refractive surgery, the errors in the correction of astigmatism are approximately 0.50 D or higher.[4–6] Even standard ablations in photorefractive keratectomy and laser in situ keratomileusis to correct myopia can induce a mean astigmatism of approximately 0.50 D.[7] Therefore, the cylindrical correction of 0.75 D or less poses a dilemma for surgeons. In cataract surgery, toric intraocular lenses (IOLs) are an option for pseudophakic patients with astigmatic corneas[8,9]; however, the possible astigmatism induced by the corneal incision and the rotational and tilt errors during IOL positioning limit the efficacy of correcting small amounts of astigmatism. For this reason, the lowest commercially available cylindrical powers in IOLs exceed 1.00 D. A common option to minimize the visual impact of residual astigmatism is to target a spherical equivalent of 0.0 D.

Published by Elsevier Inc.

0886-3350/$ - see front matter

http://dx.doi.org/10.1016/j.jcrs.2013.09.010

An important and not completely resolved practical question is to determine the minimum amount of astigmatism that has an impact on spatial vision. This would set a lower limit for practical correction, which is also affected by the accuracy of a particular correction procedure. Previous studies[10,11] found a significant reduction in visual acuity with from 0.25 to 0.50 D (depending on the visual chart used) of myopic astigmatism induced with trial lenses. However, the visual impact of small amounts of uncorrected astigmatism at best subjective focus remains controversial. This should be mainly determined by 2 aspects; that is, the optical deterioration in the retinal image[12] and the neural adaptation in the visual system.[13,14] Nevertheless, the astigmatism values to which the eye can adapt and the visual benefit of their correction have not been well determined.

In this context, we studied how small amounts of natural astigmatism (<0.5 D) and their correction affect visual acuity in a group of normal near-emmetropic subjects.

SUBJECTS AND METHODS

The study comprised healthy eyes of young subjects with astigmatism less than 0.5 D and defocus within −1.0 D to +1.0 D. The study followed the tenets of the Declaration of Helsinki. After receiving an explanation of the nature and possible consequences of the study, all subjects signed an informed consent form.

In all cases, optical aberrations and visual acuity for far were measured under natural viewing conditions (ie, no drugs were used to paralyze accommodation or dilate the pupil). The measurements were repeated 3 times; the mean value and standard deviation (SD) were calculated.

Optical Measurements and Astigmatism Correction

Wavefront aberrations were measured using a purpose-designed laboratory Hartmann-Shack wavefront sensor.[15] Zernike coefficients[16] were estimated and astigmatism was calculated and from the coefficients C(2,−2) and C(2,2). These astigmatism values were carefully corrected using a purpose-designed device that consisted of 2 rotating 0.25 D cylindrical lenses that change cylindrical power from 0.00 to 0.50 D depending on the rotation angle (α) between them. The combination gives a total cylindrical power of $0.5 \times \cos(\alpha)$, and the orientation of the axis is adjusted by rotating the whole device. The angle α is changed in 4-degree steps, inducing power changes from 0.03 D when α is 86 degrees to nearly 0.50 D when α is less than 6 degrees. Each induced astigmatic correction was subsequently verified using the wavefront sensor. This also ensured that the cross-cylinder device did not introduce significant amounts of HOAs. Astigmatism was corrected in eyes with values higher than double the estimated SD (0.065 D); that is, higher than 0.13 D. In all subjects, the residual astigmatism after correction was less than 0.07 D. From the measured wavefront aberrations, the associated eye's point-spread function was determined for each subject when defocus C(2,0) was set to zero and for 3 conditions as follows: natural astigmatism, corrected astigmatism, and astigmatism only (with all HOAs removed).

Visual Acuity Measurements

Visual acuity was measured monocularly by presenting tumbling E letters in a computer monitor with 100 candelas/m^2 luminance and placed 8 m from the tested eye. The subject's head was stabilized by a chinrest; the eye looked through an optical bench composed of a Badal optometer to allow subjective adjustment of the best focus and a system including illumination infrared light-emitting diodes, a pellicle beam splitter, and a charge-coupled device video camera to control pupil centration and size. The study was performed under normal pupil conditions. The cross-cylinder device was placed in front of the eyes to correct astigmatism. High-contrast visual acuity (100%) and low-contrast visual acuity (LCVA) (20%) were measured using tumbling E letters with natural and corrected astigmatism using the following steps: (1) The subject looked for the best subjective focus using the Badal optometer starting from a myopic position to reaching the clearest vision of a 0.4 logMAR letter. (2) The letter size was reduced up to the limit of detection. (3) This reference size and 4 other sizes (2 up and 2 down) were randomly presented in 4 orientations (right, left, up, and down). (4) Visual acuity was calculated as the letter size corresponding to 62% of the corrected responses from a psychometric function (4-parameter sigmoidal fit) of correct responses for different sizes.

RESULTS

The study evaluated 54 healthy eyes. The mean age of the subjects was 25 years ± 4 [SD] (range 19 to 35 years). Astigmatism was corrected in 47 eyes. The mean pupil diameter during visual acuity measurements was 6.4 ± 0.8 mm (range 5.0 to 8.0 mm).

Figure 1 shows the logMAR HCVA and LCVA as a function of uncorrected astigmatism and corrected astigmatism. There was a weak correlation between the increases in astigmatism and the deterioration in HCVA ($R^2 = 0.02$); LCVA did not have a correlation

Submitted: June 8, 2013.
Final revision submitted: August 7, 2013.
Accepted: September 13, 2013.

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Supported by the Ministerio de Ciencia e Innovación, Spain (grants FIS2010-14926 and CSD2007-00013), Fundación Séneca, Region de Murcia, Spain (grant 4524/GERM/06), and European Regional Development Fund (EU-FEDER).

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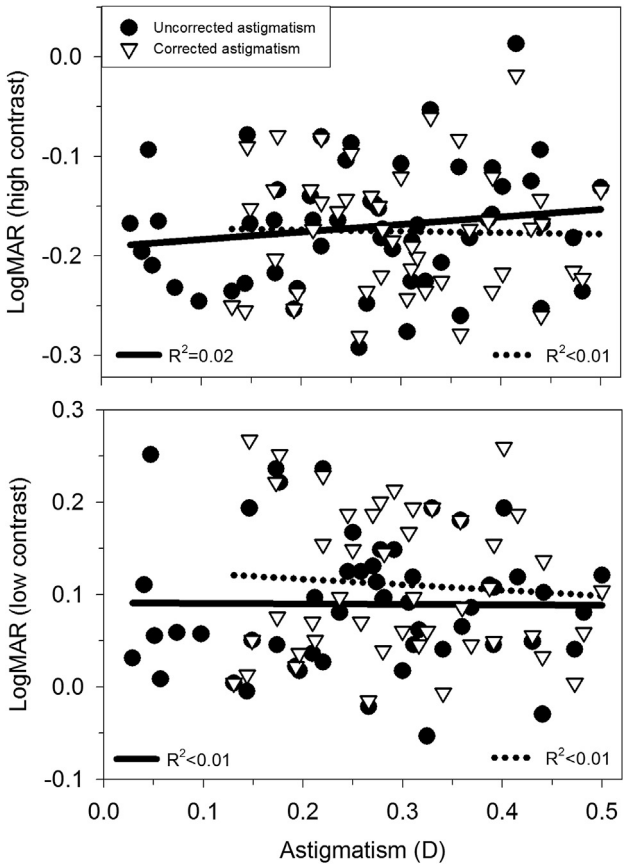

Figure 1. LogMAR HCVA and LCVA as function of ocular astigmatism with and without astigmatic correction. To create clear graphs, experimental errors are not shown. The maximum errors, expressed as the SD, were 0.065 D for astigmatism and 0.04 logMAR and 0.06 logMAR for HCVA and LCVA, respectively.

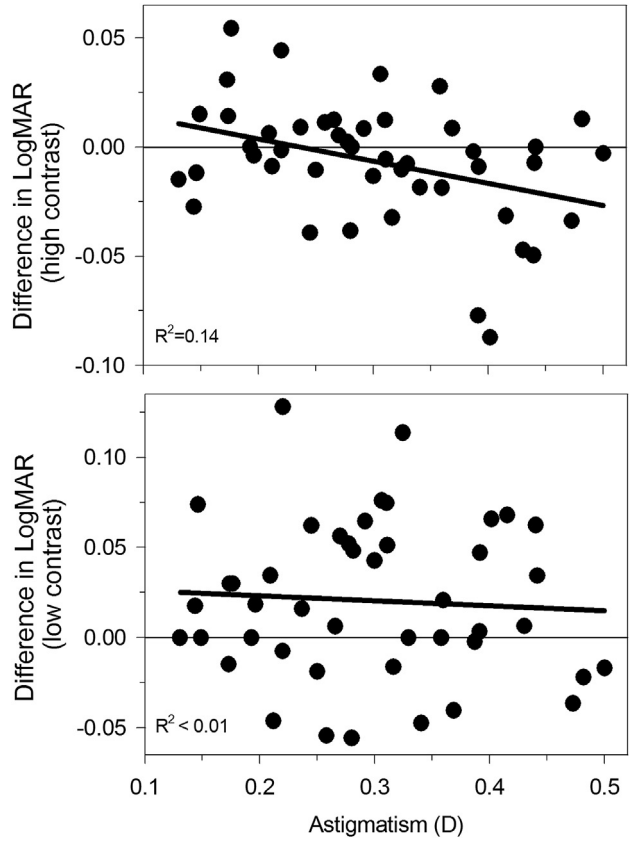

Figure 2. Changes in visual acuity with astigmatism correction (visual acuity with corrected astigmatism minus visual acuity with uncorrected astigmatism).

with astigmatism ($R^2 < 0.01$). The HCVA and LCVA varied randomly with the precorrected astigmatism values ($R^2 < 0.01$). Figure 2 shows the differences in visual acuity between corrected astigmatism and natural astigmatism. There was a relative correlation between the improvement in HCVA and the corrected astigmatism ($R^2 = 0.14$). However, the effect of astigmatism correction on LCVA did not depend on the astigmatism value ($R^2 < 0.01$).

Table 1 shows the mean HCVA and LCVA in eyes with astigmatism less than 0.3 D and eyes with astigmatism of 0.3 D or higher. Uncorrected astigmatism between 0.3 D and 0.5 D did not significantly affect the HCVA and the LCVA ($P > .50$). The HCVA after astigmatism was corrected was slightly better in the group with higher astigmatism, while LCVA was similar in the 2 groups. The benefit of correction of astigmatism on HCVA in eyes with astigmatism between 0.3 D and 0.5 D was significantly different with respect to the effect observed in eyes with less astigmatism ($P < .05$). However, the mean visual improvement was limited, with a high intersubject variability. On average, the LCVA deteriorated slightly with correction, independent of the astigmatism values and with high variation between subjects.

Figure 3 shows the optical image-quality results (logarithm of the Strehl ratio [logSR]) in all eyes under 3 conditions: all natural aberrations, corrected astigmatism, and astigmatism only. Table 2 shows these results grouped by eyes with astigmatism less than 0.3 D and eyes with astigmatism of 0.3 D or higher. When astigmatism only was considered, the optical quality decreased quickly as astigmatism increased. The inclusion of HOAs reduced the progress of the deterioration. In some eyes with astigmatism of 0.3 D or higher, there was a paradoxical result. The optical quality was better with all aberrations than with astigmatism only; that is, the HOAs improved the optical quality in eyes with astigmatism. There was a relative correlation between the degradation in optical quality and the increase in uncorrected astigmatism ($R^2 = 0.09$); this correlation was not present when the astigmatism was corrected ($R^2 = 0.01$).

Table 1. Visual acuity with natural and corrected astigmatism based on astigmatism values.

	Uncorrected Astigmatism*		Corrected Astigmatism		Difference with Correction	
VA/Astigmatism	Mean (LogMAR)	*P* Value	Mean (LogMAR)	*P* Value	Mean (LogMAR)	*P* Value
HCVA						
<0.3 D	−0.173 ± 0.055	.77	−0.170 ± 0.060	0.58	0.002 ± 0.022	0.03
≥0.3 D	−0.169 ± 0.071		−0.181 ± 0.066		−0.016 ± 0.030	
LCVA						
<0.3 D	0.092 ± 0.077	.54	0.111 ± 0.089	0.82	0.017 ± 0.044	0.79
≥0.3 D	0.080 ± 0.065		0.106 ± 0.072		0.021 ± 0.030	

HCVA = high-contrast visual acuity; LCVA = low-contrast visual acuity; VA = visual acuity
Means ± SD
*All eyes are included in the uncorrected astigmatism data. Only eyes with corrected astigmatism higher than 0.13 D are included in the corrected astigmatism data and difference with correction data.

In general, when astigmatism was corrected, the optical quality increased, but not continuously. Figure 4 shows the subjects who had an improvement in HCVA and LCVA of more than −0.02 logMAR after correction of astigmatism. Although all subjects (except 1) had improved optical-image quality, there was no correlation between the optical improvement and HCVA or LCVA.

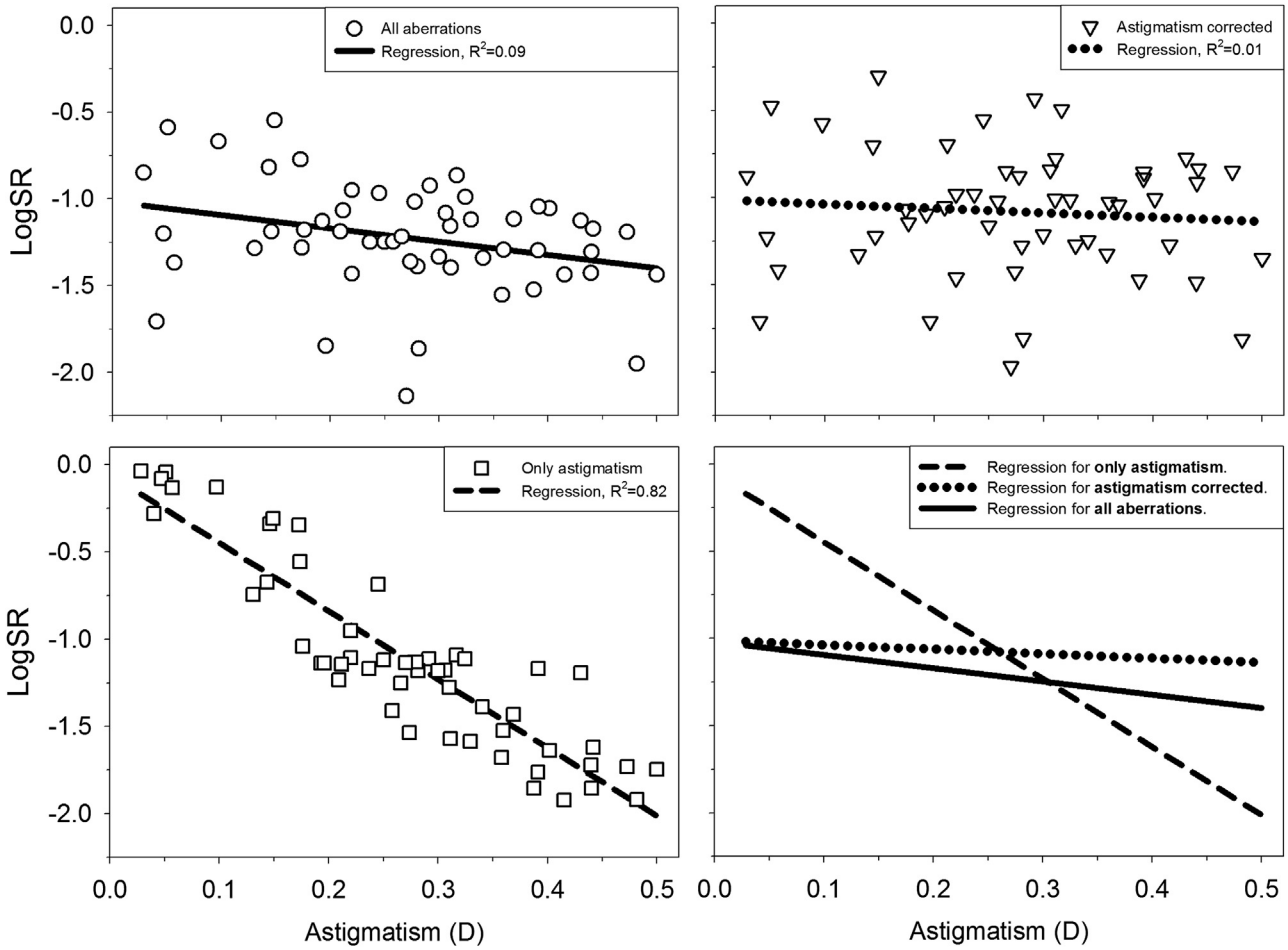

Figure 3. Optical image quality (logSR) in all eyes as function of astigmatism for 3 conditions and the regression lines for the 3 conditions (logSR = logarithm of the Strehl ratio).

Table 2. Optical image quality for 3 conditions.

	Uncorrected Astigmatism		Corrected Astigmatism		Difference with Correction		Astigmatism Only	
Astigmatism	Mean (LogSR)	*P* Value	Mean (LogSR)	*P* Value	Mean (LogSR)	*P* Value	Mean (LogSR)	*P* Value
<0.3 D	−1.195 ± 0.364	.41	−1.088 ± 0.416	.87	0.121 ± 0.149	.10	−0.821 ± 0.460	<.01
≥0.3 D	−1.268 ± 0.237		−1.072 ± 0.302		0.196 ± 0.181		−1.544 ± 0.273	

LogSR = logarithm of the Strehl ratio
Means ± SD

Figure 5 shows 3 representative examples of the optical and visual behavior in eyes in this study. In the first case, correction of 0.25 D of astigmatism improved the optical-image quality; however, the HCVA and LCVA remained the same. In the second case, the image quality, HCVA, and LCVA were slightly worse after 0.31 D of astigmatism was corrected. In the third case, the correction of 0.47 D of astigmatism improved the image quality and the HCVA and LCVA.

DISCUSSION

In this study of normal eyes, LCVA and HCVA did not depend on the precise astigmatism value when astigmatism was less than 0.5 D. Although there was some individual variability, correction of astigmatism of less than 0.3 D did not improve LCVA and HCVA. Some subjects even had a mild reduction in acuity after astigmatism correction.

The limited impact on HCVA and LCVA of the magnitude of natural astigmatism up to 0.5 D and its correction could be due to several reasons. First, we measured visual acuity at best subjective focus, which optimizes somehow the perceived image quality. This is probably the situation under normal conditions in young subjects with good accommodation capability. Second, because we performed the measurements with relatively large natural pupil diameters, the relative contribution of HOAs was larger. We also found that the aberrations reduced the reduction in image quality caused by astigmatism between 0.3 D and 0.5 D. On the other hand, the improvements in the image-quality metrics did not correlate with the measured visual acuity. This could be the result of the effect of neural adaptation to the normal aberration's pattern,[13] in particular to the small amount of existing astigmatism. In a majority of eyes, the correction of small astigmatism values (<0.5 D) further degraded LCVA. Although the main reason may be the disruption of positive coupling between astigmatism and HOAs together with neural adaptation, future studies are needed to confirm this.

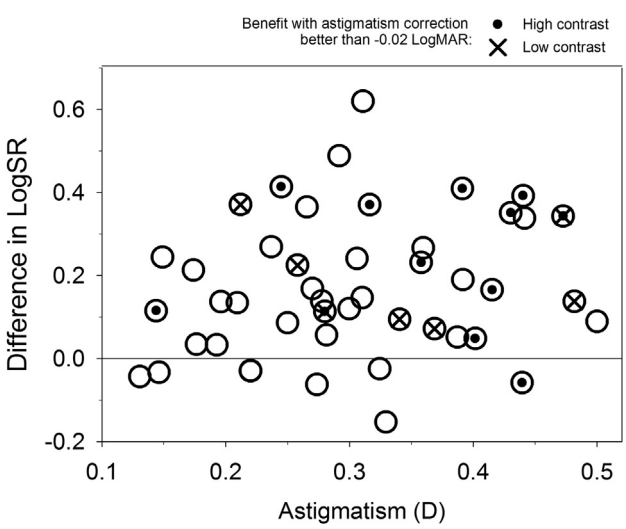

Figure 4. Changes in optical quality (logSR) with astigmatism correction showing eyes with an increase in HCVA and LCVA of better than −0.02 logMAR after astigmatism was corrected (logSR = logarithm of the Strehl ratio).

Our results may have practical implications when determining the optimum correction of astigmatism of 0.50 D or less with optical and surgical approaches. Based on our results, we would expect a relative improvement in visual acuity when correcting astigmatism higher than 0.30 D. However, this would be the case when the axis orientation of the correction is perfect. For instance, an error of 10 degrees causes residual astigmatism of 35% with a change in the orientation of 40 degrees and an additional defocus of half of the remaining astigmatism. That is, if we want to correct negative cylinder of 0.50 D, a 10-degree error would leave a residual astigmatism of 0.17 D with the axis rotated 40 degrees and an induced sphere of +0.09 D. These errors in the correction of small amounts of astigmatism could cause an adverse effect on visual acuity resulting from a breakdown in the possible neural adaptation to the orientation of astigmatism and the addition of extra hyperopic defocus.

The subjects who participated in this study and the characteristics of possible patients should also be

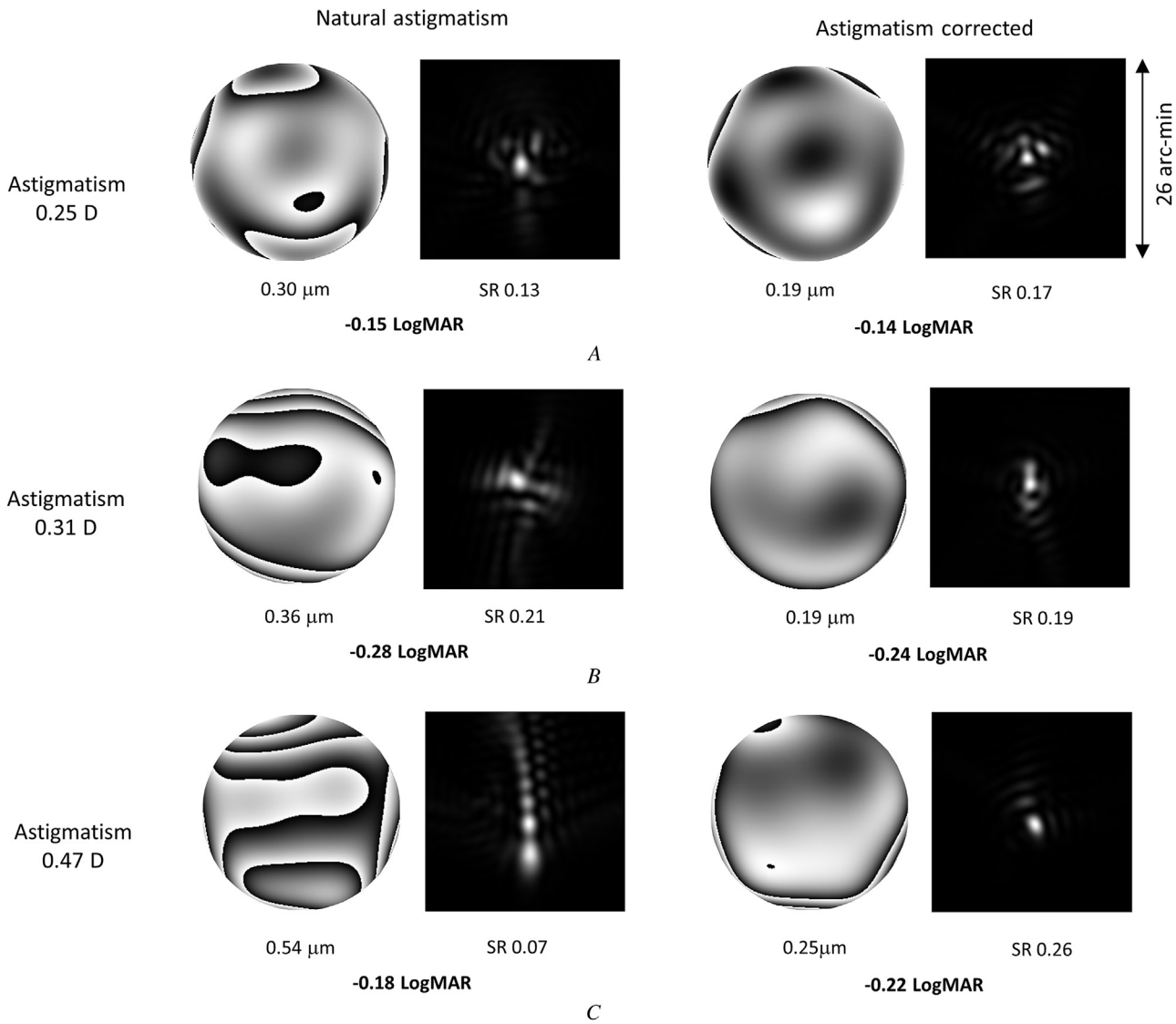

Figure 5. Examples of optical and visual behavior in 3 tested eyes with different amounts of astigmatism.

considered. Our cohort comprised healthy young adults with good vision and near emmetropia (refraction range −1.0 to +1.0 D). In refractive surgery, patients have larger refractive errors and in cataract surgery, they are usually older. Although the results should be similar, it would be interesting to extend the study to include refractive surgery and cataract surgery patients.

In conclusion, we studied the relationship between small amounts of residual astigmatism and visual acuity in a group of normal subjects. In most cases, accurate correction of astigmatism less than 0.3 D did not improve visual acuity. These results provide a solid argument to leave uncorrected small amounts of natural astigmatism, typically less than 0.5 D, in refractive and cataract surgery procedures.

WHAT WAS KNOWN

- Clinical evidence suggests the limited visual impact of the correction of small amounts of astigmatism in refractive and cataract surgery.

WHAT THIS PAPER ADDS

- Careful correction of astigmatism less than 0.3 D did not improve visual acuity in normal subjects. In many cases, visual acuity was reduced.
- These results suggest that under clinical conditions, correction of astigmatism of more than 0.5 D, but not correction of lower astigmatism, would improve visual acuity.

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