Influence of amount and changes in axis of astigmatism on retinal image quality

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We measured retinal image quality in astigmatic eyes, using the double-pass technique. We analyzed the influence of the amount of astigmatism and changes in axis of astigmatism on the eye's optical performance. Different amounts of astigmatism were obtained by variation of the cylindrical power of a lens situated in front of the eye, between 0.25-diopter (D) overcorrection and 1-D undercorrection at intervals of 0.25 D. Changes in the axis of astigmatism were obtained by rotation of the lens, which neutralizes the astigmatism in an angle of ±10° at 5° intervals. The results show the decrease in retinal image quality and the increase in the degree of image astigmatism obtained when the amount of astigmatism increases or the angle between the lens and the eye axis is other than zero. In general, the largest variations correspond to when the astigmatism changes from 0 to 0.25 D or when the axis changes from 0° to ±5°. The reduction in optical performance is smaller in living eyes than in an eye model or in an artificial eye. The aberrations present in the living eye reduce the relative loss of retinal image quality introduced by astigmatism.
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1. INTRODUCTION

Astigmatism is an aberration that in the eye can appear either because of lack of symmetry of the optical surfaces or because the images considered are outside the fovea. In the first case astigmatism gives rise to a refractive error present in most human eyes.[1,2] Clinically, this refractive anomaly is described as a bivariate quantity consisting of an astigmatic modulus and an axis.[3]

Many authors have measured the levels and the type of astigmatism exhibited by the human population.[1–6] There are various causes for change in eye astigmatism, including age and accommodation[7–14] and surgery.[15–17] Minor changes in the amount and the axis of astigmatism can also be observed in clinical practice measurements.[1,2]

Traditionally, the size and shape of the retinal image has been calculated in terms of geometrical optics. In this case the retinal image is in general a blur ellipse that degenerates into a focal line, called the Sturm focal, if the retina coincides with the image planes of one of the two meridians that exhibit the greatest or the least power, known as principal meridians. The circle of least confusion lies at the dioptric midpoint between these focals. The characteristics of the blur ellipse depend on the pupil diameter and on the type of astigmatism present.[2,18–20]

Geometrical approximation is not useful in many situations. To evaluate the influence of uncorrected astigmatism in retinal image quality, the modulation transfer function (MTF) of the eye was calculated.[18,19] Astigmatism causes a reduction in the MTF and an orientation dependence. These effects tend to increase with spatial frequency. Several studies based on visual acuity (VA) and contrast sensitivity function (CSF) measurements were also performed,[21–25] with consideration of normally spherical defocus. The results obtained showed a greater reduction in the CSF at high frequencies than at low frequencies and more sensitivity to defocus for VA than for CSF tests. When astigmatism is considered[26] some variations are reported, depending on the axis of the lenses.

The clinical test based on VA or CSF measurements can be affected by nonoptical problems in the subjects' visual system that cannot be separated from the optical ones. Therefore it seems more appropriate to perform direct optical measurements to characterize retinal image quality in astigmatic eyes. Moreover, knowledge of the retinal image quality of astigmatic eyes can allow standards of optical quality to be established for use in ophthalmic lens design.

The double-pass technique is a noninvasive objective method that permits measurement of the optical performance of the eye.[27–30] It has been used in recent years to determine the optical quality of the eye, mainly by means of the ocular MTF. The studies performed have revealed the potential of this technique in basic research[31–35] and in its application to ophthalmology, optometry, and ophthalmic optics testing.[36–41] In this study we measured the retinal image quality of astigmatic eyes by using the double-pass technique and analyzed the influence of amount and changes in axis of astigmatism on the optical performance of the eye. We also measured the retinal image quality of an artificial eye, and obtained double-pass images by numerical simulation, to compare the optical performance in these different situations.

2. METHODS

A. Apparatus

The experimental system used in this study was described in detail elsewhere.[42] It is based on the system

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developed by Santamaría *et al.*[29] and by Artal and Navarro.[30] The light coming from a He–Ne laser (632 nm, NEC Electronics) forms the image on the retina of a 20-μm pinhole, which acts as a point object; a small fraction of the light from the incident beam is reflected by the retina; and a zoom lens ($f' = 70-210$ mm) forms the aerial image of the retinal image on a CCD video camera (Pulnix Model TM-740).

One corrects the subject's spherical refractive state by moving a lens on an achromatic modified Thorner's optometer[43] placed in front of the eye. To change the amount of astigmatism we used lenses of different cylindrical power, which were situated in front of the eye in a lens holder mounted on a two-axis micrometer positioning stage that permitted a good centering of the lens. The distance between the cylindrical lens and the eye was 12 mm, and to locate the lens at a pantoscopic angle of 12° the lens holder was capable of rotating by means of a micrometer rotation stage. To vary the axis of astigmatism, we changed the orientation of the lens axis by rotating it in the lens holder, which was scaled at 5° intervals.

The exposures had a duration of approximately 100 ms. The maximum laser energy in the pupil plane for a 4-mm pupil diameter as measured in our exposures was approximately 0.02 mJ/cm^2. This level was roughly 1/200 of the maximum level allowed by the safety standards.[44]

B. Experimental Procedure

Three subjects were tested in this study: JG (male), VB (female), and JP (male), age 25, 24, and 38 years, respectively, and with different refractive states (Table 1). The subjects showed a corrected VA of 6/6 or better and were free of ocular pathology. The refractive state was measured by retinoscopy and subjective refraction. The astigmatism value was refined by the cross-cylinder method. The measurements were repeated on three different days to ensure their accuracy.

The double-pass measurements were performed with a 4-mm artificial pupil projected on the subject's pupil. Accommodation was paralyzed with two drops of tropicamide (1%) instilled 5 min apart. Every 30 min a reminder drop was also instilled. For subject JP no significant difference was found between the results obtained with the accommodation paralyzed with cyclopentolate (1%) and those obtained with the use of tropicamide (1%).

The subject's head was fixed with a bite bar that was mounted on a positioner used to align the center of the artificial pupil with the center of the subject's pupil. The subject's pupil was carefully centered by the experimenter to avoid the influence of misalignments in the optical performance of the eye.[45,46] All the data were collected in foveal vision, and the point source was used as a fixation target.

Table 1. Refractive State of the Three Subjects Studied

Subject	Spherical Ametropia	Total Astigmatism
JG	−2.75 D	−1.00 D × 10°
VB	+0.25 D	−0.25 D × 0°
JP	+0.75 D	−0.75 D × 100°

To study the influence of the amount of astigmatism on retinal image quality we started the measurements at optimum focus, which we obtained by moving the lens of the modified Thorner's optometer, and with optimum astigmatic correction, provided by a spherocylindrical lens. In these conditions, the subject focuses the point source on the retina. If a minor residual astigmatism exists, the subject looks for focusing on the circle of least confusion. Without changing this focal condition, we varied the cylindrical lens power between 0.25-diopter (D) overcorrection of the astigmatism and 1-D undercorrection, at 0.25-D intervals. In these cases the retinal image of the point source is a Sturm focal. To analyze the influence of the changes in axis on retinal image quality we rotated the lens, which neutralized the astigmatism within an angle of $\pm 10°$, at 5° intervals.

The short-exposure aerial images recorded were averaged on the computer to remove the speckle (coherent noise), and we took two series of eight exposures each, thus averaging 16 frames. For one subject (JP) we verified that there was no significant difference between averaging 16 and averaging 32 frames. The images were 256×256 pixels with 8 bits/pixel, and the final averaged image had 16 bits/pixel. A background image, which we obtained by placing a black diffuser in the pupil plane instead of in the eye, was subtracted from the aerial images.

C. Modulation Transfer Function

The MTF was computed as the square root of the modulus of the Fourier transform of the aerial image. The aerial images contained a near-uniform remaining background produced by ocular and retinal scattering, corneal reflex, and light coming from the experimental setup that had not been eliminated. This background produced a peak at zero frequency in the modulus of the Fourier transform of the aerial images, and, since the MTF for zero spatial frequency was normalized to value 1, all values at other frequencies were reduced. To overcome this limitation we used a procedure proposed by Artal and colleagues[32,33,35] that consists of removing all the values in the MTF lower than 3 cycles per degree (c/deg) and extrapolated these values, using an exponential function.[40] We recalculated the MTF by dividing the function by the extrapolated value at zero spatial frequency. Since the MTF should be zero for spatial frequencies larger than the diffraction-limited value, we calculated the average value in the MTF for these frequencies, subtracted that value, and renormalized to obtain the MTF.

D. Image Quality Parameters

To easily compare retinal images or their MTF's,[1] it is useful to have a single parameter that evaluates the overall image quality. From each double-pass image we computed several image quality parameters. We computed two types of parameters to analyze the retinal image quality: (1) the ratio between the maximum and the mean irradiance value of each image; and (2) the volume under the aerial image, with consideration of the complete image or regions contained in concentric circles of radius 1.5, 3, and 10 arc min. The quotient between maximum and mean irradiance and the volume total give practically the same results. These results are similar to those obtained when circles of radius 5 or 10 arc min are considered. For 1.5 and 3 arc min, differences appear. We use the quotient between maximum and mean irradiance as the retinal image quality parameter. This is one of the most discriminatory parameters.

We also computed two kinds of parameters to analyze the degree of astigmatism of the retinal image: (1) the ratio between the areas under the retinal image profile and those under the MTF profile, corresponding to the orientation of the principal meridians, which show maximum and minimum elongation of the double-pass image; and (2) the ratio between the MTF values at a fixed spatial frequency (3, 6, and 12 c/deg) in these orientations. The quotients between the areas under the MTF profiles and double-pass images profiles are highly sensitive to small differences in the profiles and are therefore also highly sensitive to the degree of astigmatism.

E. Numerical Simulations and Artificial Eye

We calculated the optical performance of a theoretical eye by numerical simulation, using an emmetropic eye model with aspherical surfaces.[47] Astigmatism was simulated with the parameters of the cylindrical lenses used in the experimental measurements. We also obtained the optical performance of an artificial eye, formed by an achromatic spherical lens ($f' = 50$ mm) and a diffuser, which was rotated to avoid the influence of speckle. Different amounts of astigmatism were obtained by placement of lenses of spherical power equal to zero and different cylindrical power in front of the artificial eye with their axis at 0°. Except for the case of 0.25-D overcorrection, the lenses were the same as those used to correct the living eyes.

3. RESULTS

A. Amount of Astigmatism

Figure 1 shows a series of double-pass images calculated by numerical simulation [Fig. 1(a)] and those obtained in the artificial eye [Fig. 1(b)] and in a living eye [subject JG, Fig. 1(c)], corresponding to different values of astigmatism. A negative value means overcorrection, and a positive value means undercorrection. These results are presented as gray-level images. This figure gives a qualitative picture of how retinal image change with the amount of astigmatism. The images obtained by simulation are smaller and more concentrated than are the images corresponding to the artificial eye; i.e., they have higher optical quality. These differences may be due to the fact that, for the artificial eye, exact focusing of the image is more difficult than for eye simulation. In this case we found an important influence in the retinal image quality, that of small changes in the position of the image plane, and we chose the best focus condition. When these images are compared with images for the living eye (Fig. 1) there are considerable differences in shape and size because of the eye's optical performance.

Figure 2 presents the image quality parameters used to evaluate the overall image quality and the degree of astig-

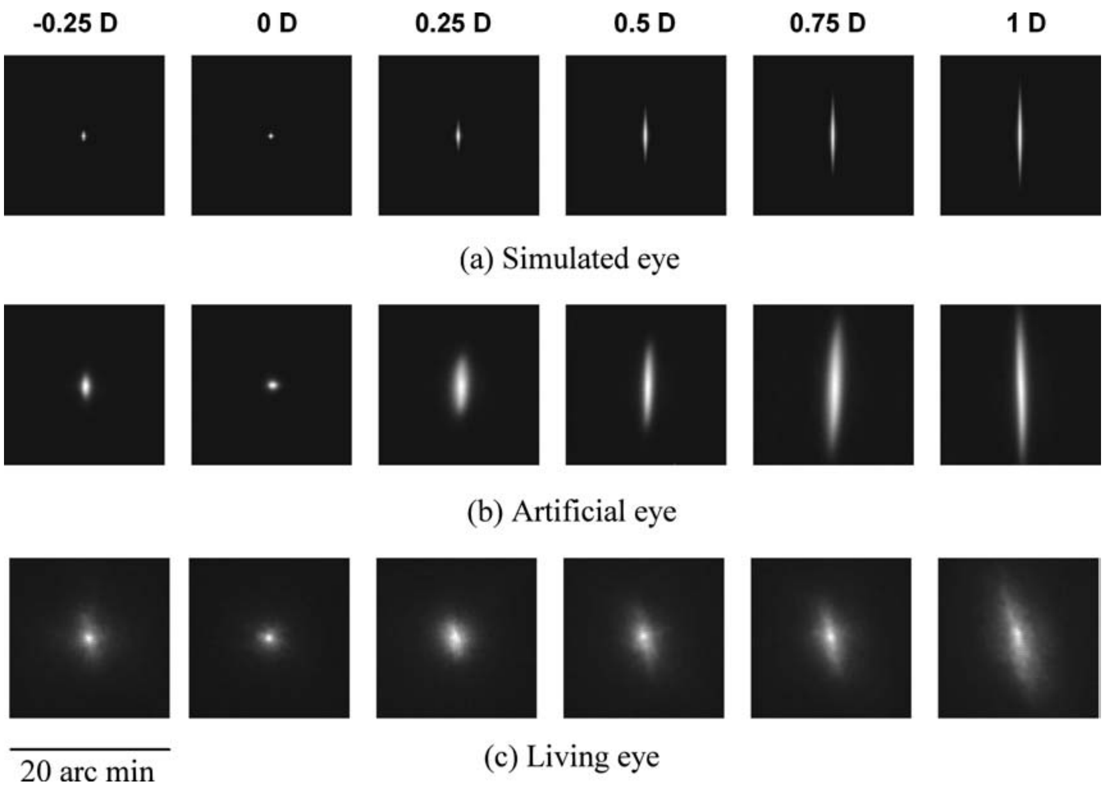

Fig. 1. Double-pass images (a) numerically simulated in an eye model, (b) measured in an artificial eye, and (c) measured in a living eye (subject JG) for different amounts of astigmatism. Negative values of astigmatism mean overcorrection, and positive values mean undercorrection.

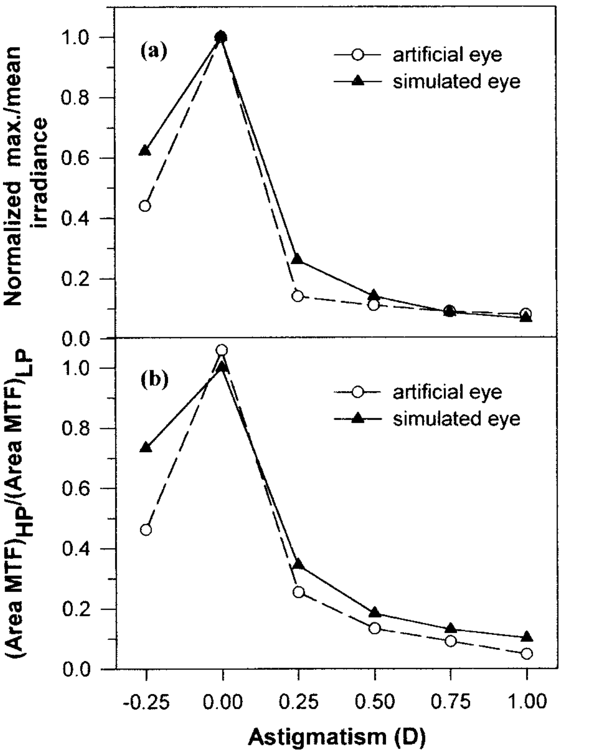

Fig. 2. (a) Normalized maximum divided by the mean irradiance of double-pass images, and (b) quotient of the areas of the MTF profiles corresponding to the 0° and 90° directions obtained in an artificial eye and by numerical simulation, as a function of astigmatism.

matism of the retinal image corresponding to the images obtained in the artificial eye and by numerical simulation. Figure 2(a) shows the normalized maximum in the image divided by the mean irradiance, and Fig. 2(b) shows the quotient of the areas under the MTF profiles corresponding to 0° and 90° directions, as a function of astigmatism. We chose these directions because astigmatism is induced in the artificial eye and in the simulation with an axis of 0°, and therefore these directions are equivalent to the principal meridians of the eye.

The behavior of the artificial and the simulated eye was similar, but the image quality was slightly better for the simulated eye. The largest decrease in retinal image quality occurred when astigmatism appeared. For both the artificial eye and the simulated eye, quality was lower in the 0.25-D case than for −0.25 D. To simulate the two cases we used lenses without spherical power, but for 0.25 D the cylindrical power was negative, and for −0.25 D it was positive. The different geometry of these lenses may explain the differences in retinal image quality. Finally, the quotient of the MTF profile areas [Fig. 2(b)] greater than 1 obtained for 0-D astigmatism in the artificial eye may be due to the difficulty of exactly focusing the image.

Figure 3 presents, for the three subjects studied and for the simulated eye, the normalized maximum divided by the mean irradiance as a function of the amount of astigmatism. In general, as for the eye model and the artificial eye, the largest decrease in retinal image quality corresponded to the change from 0 to ±0.25 D, i.e., to the appearance of astigmatism. For subject VB there was also a large decrease in retinal image quality when the astigmatism changed from 0.25 to 0.5 D. For subject JG and for the −0.25-D case retinal image quality is practically the same as for the simulated eye. In this case the lens used in eye simulation and in the living eye are different.

We computed the MTF from the average aerial images as explained above. Figure 4 shows the MTF profiles in the direction of the low-power (solid curve) and high-power (dotted curve) principal meridians corresponding to the three subjects considered, when astigmatism was 0 and 1 D. These profiles show the minimum and maximum effects of astigmatism: The lower curve corresponds to the orientation showing the maximum elongation of the aerial image, while the upper curve corresponds to the minimum elongation.

When the astigmatism was compensated (0 D) the profiles were practically the same. The subjects showed a slight difference and therefore a small degree of astigmatism on the retinal image, which might be due to the astigmatism's not being fully compensated by the lens and the subject's not focusing exactly on the circle of least confusion. For 1 D (Fig. 4) the degree of astigmatism obviously increased. When results for the three subjects are compared JP shows the lowest degree and VB the highest.

The quotient between areas of the MTF profiles corresponding to high- and low-power principal meridians for the three subjects studied and for the simulated eye are shown in Fig. 5. For subjects VB and JP we obtained values of this retinal image quality parameter higher than 1 for 0 D and lower than one in the other cases. This means that the maximum or minimum elongation of the aerial image corresponded to different principal meridians and that therefore the astigmatic image had changed orientation. These changes may have been due to the subject's not focusing exactly on the circle of least confusion at 0 D. In general, the degree of astigmatism increases with the astigmatism value, and therefore the quotient between the two areas decreases. However, there are some cases in which this quotient increases when astigmatism increases, especially for subject JP when astigmatism changes from 0.5 to 1 D. We repeated

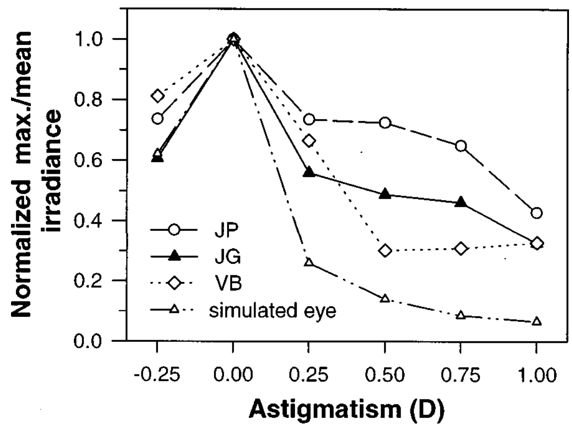

Fig. 3. Normalized maximum divided by the mean irradiance of retinal images as a function of astigmatism for the three subjects analyzed (JG, VB, and JP) and for a simulated eye.

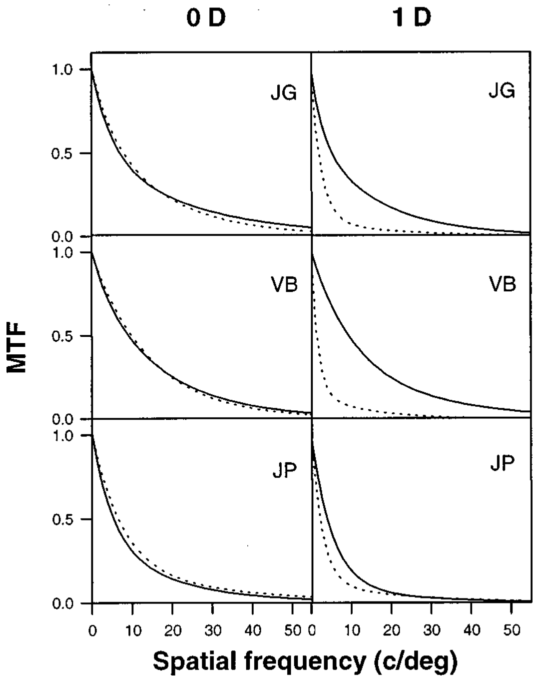

Fig. 4. MTF profiles in the direction of the low-power (solid curve) and the high-power (dotted curve) principal meridians, for the three subjects considered and for astigmatism of 0 and 1 D.

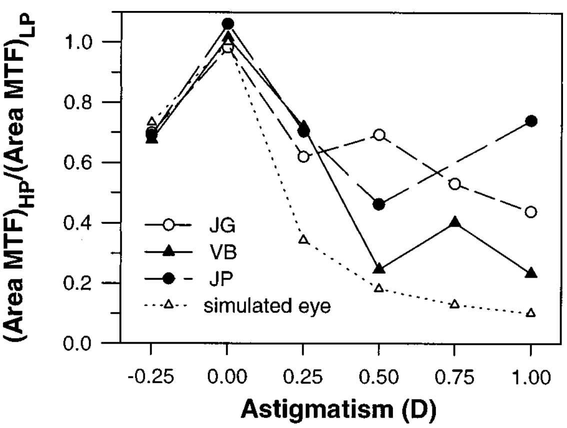

Fig. 5. Area under the MTF profile corresponding to the direction of the high-power principal meridian divided by that corresponding to the direction of the low-power principal meridian, for the three subjects considered and for a simulated eye, as a function of the astigmatism.

these measurements several times and always obtained this surprising result.

To extract one-dimensional data sets from a bidimensional MTF[39] we obtain the average profile by averaging the MTF over all orientations. Figure 6 shows the MTF average profiles for the three subjects studied, when astigmatism was 0, 0.25, and 1 D. Differences increase with defocus, and there is a greater reduction in the MTF at high frequencies than at low frequencies.

Figure 7 shows the MTF average profiles for the simulated eye, the artificial eye, and the living eye (subject JG) when the astigmatism was 0 and 1 D. For astigmatism of 0 D the highest optical performance is obtained for the eye model and the lowest is obtained for the living eye. This means that, when there is no dioptric blur in the retinal image, the aberrations present in the living eye are greater than for the eye model. For astigmatism of 1 D the optical performance of the living, artificial, and simulated eyes are more similar than for 0-D astigmatism. In this case the dioptric blur associated with this amount of astigmatism is the greatest aberration.

B. Changes in Axis

To evaluate the influence of a variation in the axis of astigmatism on retinal image quality we placed in front of the eye a lens whose cylindrical power was suitable for correcting the astigmatism and whose axis formed a particular angle with the axis of the astigmatic eye. Because of this angle, the system formed by the correcting lens and the eye will have a residual spherocylindrical power.[48,49] Table 2 shows the residual spherocylindrical power for the three subjects analyzed and for the values of the angle formed by the lens and eye axis considered. In the case studied, i.e., when the lens corrects the astigmatism, the cylindrical power of the eye C_e and the cylin-

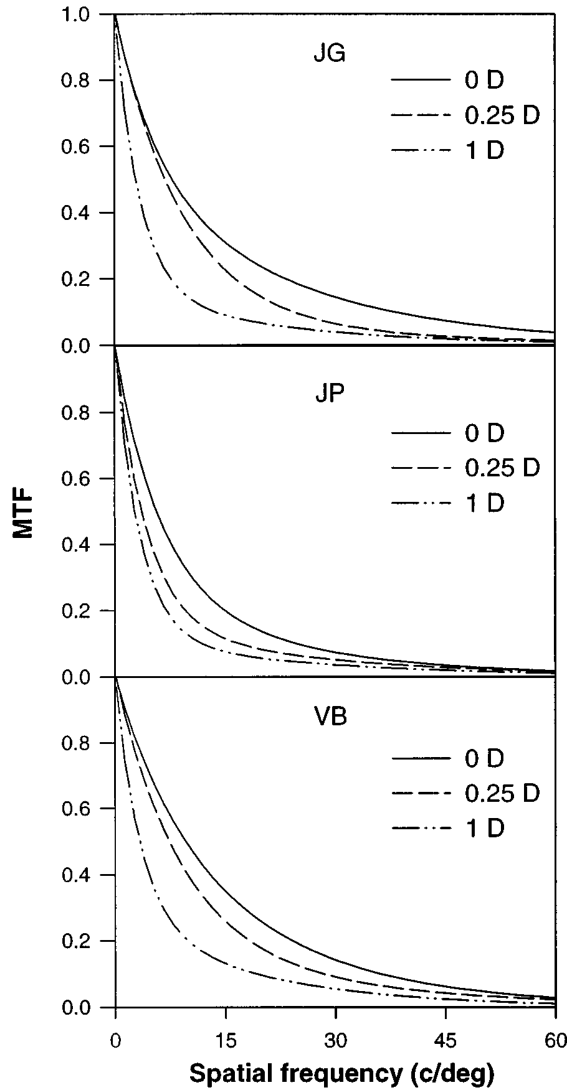

Fig. 6. MTF average profiles for the three subjects studied and astigmatism amounts of 0, 0.25, and 1 D.

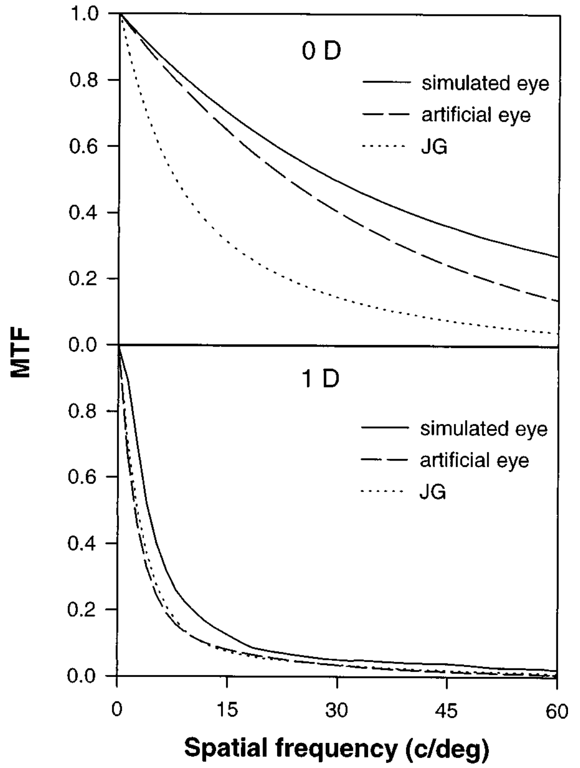

Fig. 7. MTF average profiles for a simulated eye (solid curve), an artificial eye (dashed curve), and a living eye (subject JG, dotted curve) at 0 and 1 D values of astigmatism.

Table 2. Residual Spherical–Cylindrical Power Obtained When the Axis of a Lens Correcting the Astigmatism of an Eye Formed Different Angles with the Axis of the Astigmatic Eye[a]

Subject	θ	S	C	α
VB	10°	0.04 D	−0.09 D	140°
	5°	0.02 D	−0.04 D	137.5°
	−5°	0.02 D	−0.04 D	42.5°
	−10°	0.04 D	−0.09 D	40°
JP	10°	0.13 D	−0.26 D	60°
	5°	0.06 D	−0.13 D	57.5°
	−5°	0.06 D	−0.13 D	142.5°
	−10°	0.13 D	−0.26 D	140°
JG	10°	0.17 D	−0.35 D	150°
	5°	0.09 D	−0.17 D	147.5°
	−5°	0.09 D	−0.17 D	52.5°
	−10°	0.17 D	−0.35 D	50°

[a] Results are shown for the three subjects who took part in the experiment. θ is the angle formed by the lens and the eye axis, S is the residual spherical power, C is the residual cylindrical power, and α is the axis of the residual refractive error.

drical power of the lens C_L verify that $C_e = -C_L$, and the residual spherical power E and the residual cylindrical power C verify that $E = -C/2$ for any angle formed by the eye and lens axis. This means that in the geometrical approximation the retinal image corresponds to the circle of least confusion.

According to Table 2, the retinal image quality must decrease when the angular change in axis of astigmatism increases. For the same angular value, the greatest variation is expected for subjects with a higher residual refractive error (JP, JG).

In Fig. 8 the normalized maximum divided by the mean irradiance is plotted for the three subjects studied as a function of the angle formed by the lens and the astigmatic eye axis. For this quotient the largest variations are obtained when the angle formed by the axis of the lens and the axis of the astigmatic eye changes from 0° to ±5°. This behavior is similar to that found in Fig. 3, in which the largest variation occurs when the astigmatism changes from 0 to ±0.25 D.

For the same angular value, the results obtained for the three subjects studied do not clearly show the variations expected from the geometrical approximation. This is probably because the aberrations of the living eye are greater than the defocus produced for the small residual spherocylindrical power obtained for the angles considered.

Figure 9 shows the quotient between the areas under the highest and those under the lowest MTF profiles as a function of the angle formed by the lens and the astigmatic eye axis. Since the retinal image lies in the circle of least confusion, no orientation dependence is expected for this image in the geometrical approximation. However, calculations considering a diffraction-limited eye or a real eye[18] show an orientation dependence in the circle of least confusion that increases with the amount of astigmatism. No exact focusing on the circle of least confusion at 0 D contributes to image orientation dependence. For subject VB there was little variation in the degree of astigmatism. It is important to take into account that the parameter plotted is highly sensitive to small differences in the profiles. Quotients of the areas under the MTF profile can be greater than 1 for 0° and lower than 1 for other angles because for 0° one obtains the quotient of areas by dividing profiles corresponding to high-power principal meridians by the profile corresponding to low-power principal meridians, and, for other angles, the quotient is between profiles corresponding to the orientation of maximum and minimum elongation of aerial images.

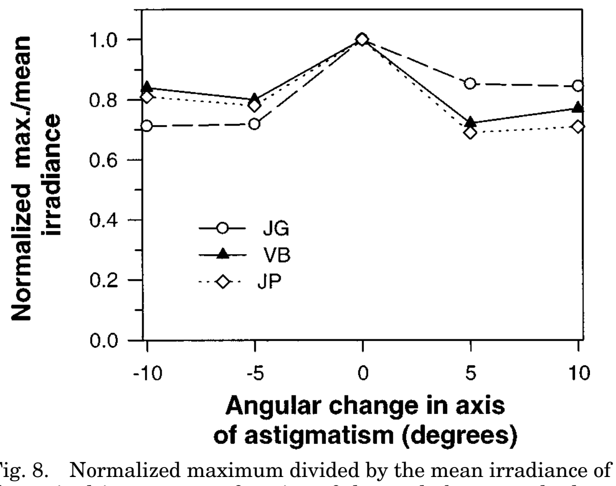

Fig. 8. Normalized maximum divided by the mean irradiance of the retinal images, as a function of the angle between the lens and the astigmatic eye axis, for the three subjects analyzed.

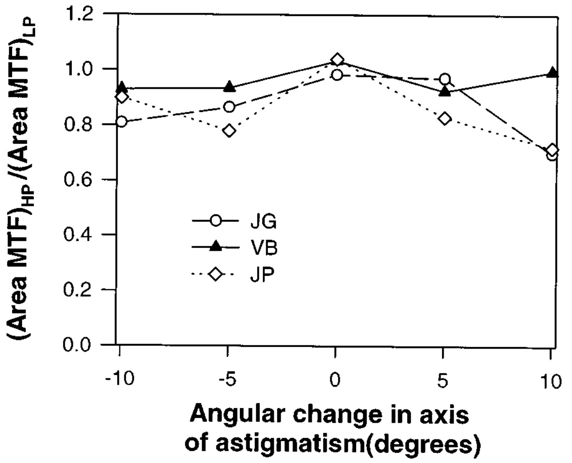

Fig. 9. Quotient between the areas under the MTF profiles corresponding to the directions of maximum and minimum elongation of aerial images for the three subjects considered, as a function of the angles formed by the lens and the astigmatic eye axis. (For the 0° case, the directions considered are those corresponding to the lowest- and highest-power principal meridians).

Subject JG shows a similar degree of astigmatism for images corresponding to 0° and +5°. Similarities in the degree of astigmatism for two angles and differences for the other angles may mean that the correct axis for astigmatism compensation is between the two angles that present similarities.

4. DISCUSSION AND SUMMARY

The main objective of this study was to perform direct optical measurements to characterize retinal image quality in astigmatic eyes under conditions that allow the analysis of the influence of the amount and changes in axis of astigmatism on that image. We used the double-pass technique,[27–30] a noninvasive objective method for recording the retinal image, which has been shown to be useful for evaluating the optical performance of the eye in several situations.[31–42] Images were obtained in optimum spherical correction. To change the amount of astigmatism we used lenses of different cylindrical power, with the retinal image lying on one Sturm focal. To vary the axis of astigmatism we changed the orientation of the lens axis, with the retinal image lying on the circle of least confusion. According to the geometrical approximation, the size of the retinal image is proportional to the amount of astigmatism. However, this approximation is not useful in general for studying imagery in astigmatic cases.

Considering an emmetropic eye model or an artificial eye, we found that the variation of retinal image quality with amount of astigmatism is not uniform. The results obtained [Fig. 2(a)] show a larger decrease in retinal image quality when astigmatism appears. In geometrical approximation this decrease is expected because it indicates the degeneration of a point image to a Sturm focal. The variations for other values of astigmatism are much lower.

Experimental measurements obtained in living eyes (Fig. 3) also show that, generally, the largest decrease in retinal image quality corresponds to the appearance of astigmatism. However, this decrease and the variation in other values of astigmatism are lower than those obtained with an eye model and an artificial eye. The aberrations in living eyes introduce an additional blur into the retinal image that tends to reduce the loss of retinal image quality introduced by astigmatism.

The most important changes in the degree of astigmatism of the images also occur when the astigmatism appears [Figs. 2(b) and 5]. In a living eye the variations are lower than in an eye model or in an artificial eye (Fig. 5) because of the presence of other aberrations besides astigmatism.

To evaluate the optical performance with a one-dimensional data set for each amount of astigmatism, we calculated average profiles of the MTF. Astigmatism reduces the optical performance in an eye model, an artificial eye, and a living eye (Figs. 6 and 7), but in different proportions. The reduction of optical performance because of astigmatism is higher in a high-quality eye (an eye model) than in an aberrated eye (a living eye).

When a spherocylindrical lens to correct the astigmatism is placed in front of the eye, with an angle formed by the lens and the eye axis other than zero, the lens–eye system has a residual spherocylindrical refractive error. This situation can be created in clinical practice when the correction axis and the eye axis are not coincident. In this case measured retinal image quality decreases when the angle formed by the lens and eye axis increases, as is expected according to geometrical approximation, and the largest variations correspond to when the angle changes from 0° to ±5°. This behavior is similar to that obtained for the variations in amount of astigmatism. For the same angular value the results obtained do not show the proportional dependence on the residual refractive error expected from the geometrical approximation. Again in this case, the monochromatic aberrations present in the living eye reduce the contribution of the residual spherocylindrical power to the diminution of retinal image quality.

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