Comparison of the Optical Image Quality in the Periphery of Phakic and Pseudophakic Eyes

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Purpose. The natural lens may provide some compensatory optical effect in the periphery. When it is substituted by an IOL during cataract surgery, the quality of the peripheral optics will be modified. We compared the peripheral image quality in the eyes of patients with one eye implanted with a monofocal IOL and the fellow eye still with the natural precataract lens.

Methods. We used a scanning peripheral Hartmann-Shack wavefront sensor to measure the central 80° of visual angle along the horizontal meridian. Twelve patients with ages ranging between 65 to 81 years were evaluated. The results of the phakic and pseudophakic eyes were compared using the spherical equivalent, astigmatism, higher order aberrations, and the Strehl ratio. The statistical differences at each angle between the two eyes were evaluated.

Results. In the eyes implanted with IOLs, the peripheral mean spherical equivalent was slightly more myopic than in the phakic eyes, although the differences were only significant for some angles. Astigmatism increased much faster in the periphery for the pseudophakic eyes as compared with the phakic eyes. The mean values were significantly different from 9° and 17° outwards at the temporal and nasal retina, respectively. As an example, at 30°, eyes implanted with IOLs presented 1.5 diopters (D) of additional astigmatism. The higher order aberrations were not significantly different between the two groups.

Conclusions. Eyes implanted with monofocal IOLs present more astigmatism in the periphery than the healthy older eyes. This suggests that the crystalline lens provides a beneficial effect to partially compensate off-axis astigmatism. The degradation of the peripheral retinal image may reduce the pseudophakic patient's performance in common visual tasks.

Keywords: peripheral optics, intraocular lenses, aberrations, refractive errors

Although, during the last decade, peripheral optics research of the eye has been mainly motivated by myopia research,[1–3] the fundamental relationship between the optical and visual resolution in the periphery has also been studied.[4–6] A limiting factor in this field has been the lack of an adequate optical instrumentation.[7] Traditionally, instruments developed for central measurements were used sequentially for a number of eccentric fixations. The recent introduction of scanning sensors[8,9] has allowed fast and reliable measurements of the off-axis optical quality.

The application of these instruments created the opportunity to examine other interesting topics related to off-axis optical quality of the human eye. Although peripheral vision has been considered to be secondary to foveal vision, its importance should not be underestimated in different visual tasks. We are especially interested in the impact of peripheral optics on visual performance in subjects with modified optics, in particular post cataract patients. In this regard, patients implanted with IOLs are a large group where peripheral image quality has not been extensively studied.

Cataracts are successfully treated by replacing the crystalline lens, which has become opaque, by an artificial IOL. The increase of life expectancy means that people continue to live for many years after cataract surgery and are still very active in the society. This increases the demands on the optical quality of the IOLs and the refractive surgery, to aim for a postoperative vision of equal quality as the healthy eye. Since the eye is an example of optimized optical design,[10] it would be likely that the crystalline lens could provide some protection for the peripheral degradation. In recent years, there have been developments to modify the optical properties of IOLs from standard spherical lenses to aspheric lenses to mimic the crystalline lens in the younger eye.[11–15] It makes sense to further explore designs of IOLs replicating the optics in the healthy young eye by also considering the optical properties in the peripheral retina.

The peripheral quality of eyes implanted with IOLs has been scarcely investigated. Smith and Lu,[16] examining the issue theoretically, found that the peripheral power errors and the oblique astigmatism of pseudophakic eyes were larger than in phakic eyes. The importance of the crystalline lens on peripheral refraction was also addressed by Millodot,[17] who measured aphakic eyes with a refractometer and compared them with the results of healthy control eyes of people with similar ages. More recently, peripheral refraction has been also measured with a scanner photoretinoscope.[18] Mathur and Atchison[19] measured peripheral aberrations in patients implanted with spherical IOLs for some locations in a relatively small field of view.

In this context, the main aim of this study was to measure, in vivo, the peripheral optical quality in the eyes of patients implanted with an IOL after cataract surgery and to compare it

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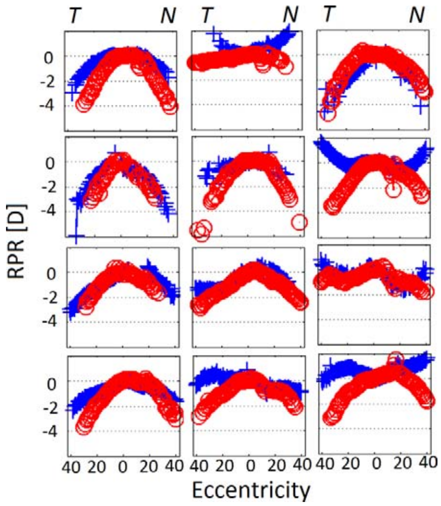

Figure 1. RPR for the 12 patients. The *crosses* give the results for the healthy eye and the *circles* represent the operated eyes. *T* and *N* are respectively indicating temporal and nasal retina.

with the precataract fellow eye. The results could serve as a guide to replicate the off-axis performance of the natural optics in future IOL designs.

Methods

A laboratory prototype of a fast peripheral Hartmann-Shack (HS) wavefront sensor scanner was used to measure the wave aberration of the central 80° of the horizontal meridian in phakic and pseudophakic eyes. The details of the instrument are given elsewhere.[9] It can sample the whole angular range in 1.8 seconds with a density of 1 measurement per degree. To improve the comfort of the subject the positioning was done by means of a head–chin rest. A red dot at a 2 m distance was the fixation target. Four consecutive scans were taken. The scans were examined for anomalies due to external errors, if one scan was erroneous it was omitted from the measurement, and if two or more were bad, the measurement was not used for further analysis. Since the scans were typically not significant different from each other,[9] the mean of the four scans was used when examining the data.

Both eyes of 12 subjects (72 ± 7.5 years; 6 males/6 females; average refraction: 0.7 ± 1.5 diopters [D] defocus and −1.1 ± 0.7 D cylinder) were measured. All subjects had one operated eye and the other eye either healthy or with limited cataract. The operated eye was implanted with a standard spherical monofocal lens of different brands and different powers. All subjects had 20/20, or better, corrected visual acuity in the operated eye. Although either some degree of cataract in the nonoperated eye or secondary cataract in the operated eye could be present, this was minimized in the selected patients. We used, as an objective approach, the evaluation of the HS images at different eccentricities. In both eyes, these images appeared only minimally affected by a significant amount of scatter. We did not include in the study patients showing an elevated ocular scatter. This approach assured us that the selection was consistent with normal operated and ageing eyes (in some cases with early symptoms of cataracts). The measurements were taken under natural conditions without pupil dilatation. The whole pupil size of the subject was taken into account when fitting the Zernike polynomials. The coefficients were mathematically rescaled to a reference pupil with a diameter of 3 mm. This size was chosen to ensure that even at the largest eccentricities, the minor radius of the off-axis elliptic pupil shape was larger than the reference pupil size. Because the measurements were done under dim light conditions, all patients fulfilled this criterion.

To compare the image quality of the pseudophakic eye with the healthy elderly eye, different optical parameters were tested. The metrics 'mean spherical equivalent' (M) and astigmatism (J0), both in diopters, were examined in the comparison. These were calculated from the corresponding low order Zernike terms. Further, the root mean square of the higher order aberrations (HOA-RMS) was calculated from the third and fourth order Zernike coefficients of the 3-mm pupil and expressed in microns. To quantify the overall retinal image quality, the point spread function (PSF) for each subject at each angle (taking into account a cosine variation of the pupil shape with eccentricity) was also calculated. Then, the Strehl ratio, defined as the ratio between the maximum intensity of the simulated retinal image and the maximum intensity of the diffraction-limited retinal image, was determined for each angle. To facilitate the visual comparison between the pseudophakic and the phakic eye results, the metrics were

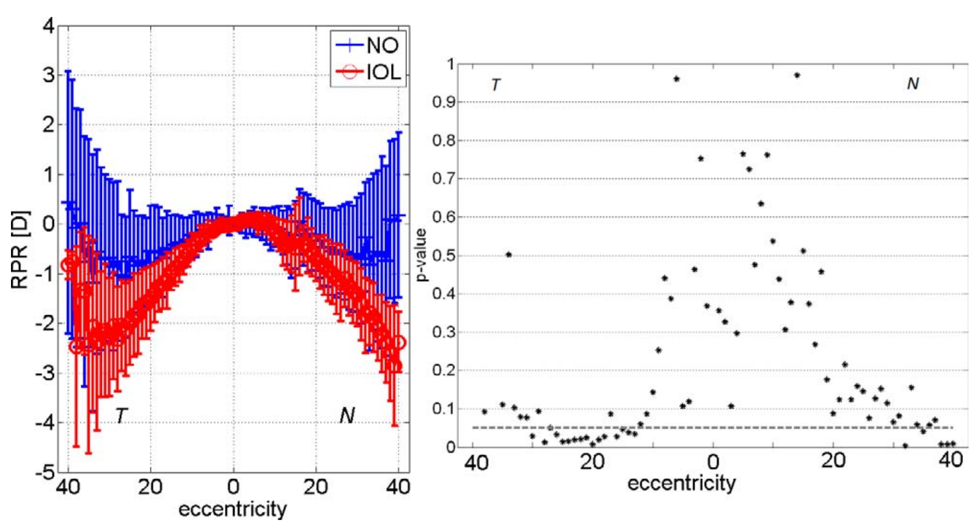

Figure 2. (*Left*) Mean and SD of the relative peripheral refraction between the healthy eye (NO) and the operated eye (IOL). (*Right*) The angles at which groups are significantly different are the *stars* which fall *below* the *striped line*.

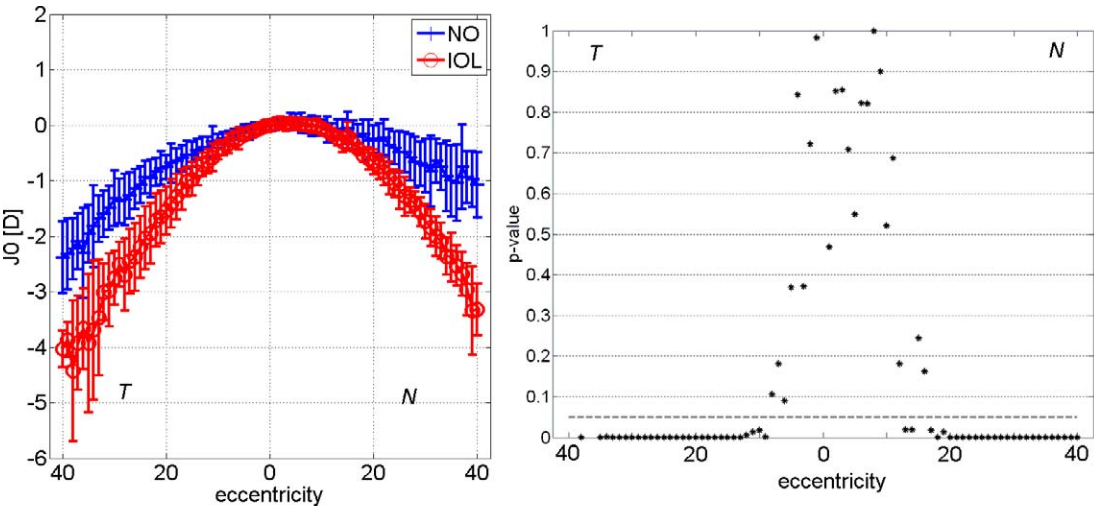

Figure 3. (*Left*) Mean and SD of the relative oblique astigmatism between the healthy eye (NO) and the operated eye (IOL). (*Right*) The angles at which both groups are significantly different are the *stars,* which fall *below* the *striped line*.

normalized to the foveal value. A paired *t*-test was used at each angle to investigate whether the operated and the nonoperated eye were significantly different.

The use of the sensor and the experiment followed the tenets of the Declaration of Helsinki. All subjects were fully informed before participating in the study.

Results

The difference in M between the healthy eye (NO) and the operated eye (IOL) for each of the 12 subjects is presented in Figure 1. The shape of the relative peripheral refraction (RPR) was found for most patients to be similar. However, some of them, as for example numbers 2, 6, and 12 (Fig. 1), were relatively more myopic in the periphery in their operated eye. The mean and the SD for the whole population are given in Figure 2 (left). Figure 2 (right) gives the *P* value of the paired *t*-test comparing the operated and the nonoperated situation at each eccentricity angle. The angles with a *P* value below 0.05 were considered significantly different. At the temporal retina some angles were significantly different, but a strong trend was not observed. In general, an eye implanted with an IOL tended to have slightly more relative peripheral myopia compared with a healthy eye.

The results of J0 were uniform across all subjects. They showed larger amounts of astigmatism with eccentricity in the operated eye as compared with the healthy eye. Figure 3 gives the mean and the SD of the normalized J0 (Fig. 3, left) and the *P* values (Fig. 3, right). Already for angles of 10° temporal retina and 15° nasal retina the operated eyes had significantly more astigmatism. At 40°, most subjects had between 1 D and 1.5 D more J0 in their operated eye compared with the healthy eye.

Figure 4 shows the RMS of the high order aberrations as a function of eccentricity for the two groups. The average magnitude and tendency of the aberrations appeared to be similar in both eyes.

Figure 5 shows the average Strehl ratio as a function of eccentricity for both groups. The impact of the IOL on astigmatism was dominant in the degradation of the overall retinal image quality, considering the small differences in high order aberrations. Peripheral retinal image quality of an eye

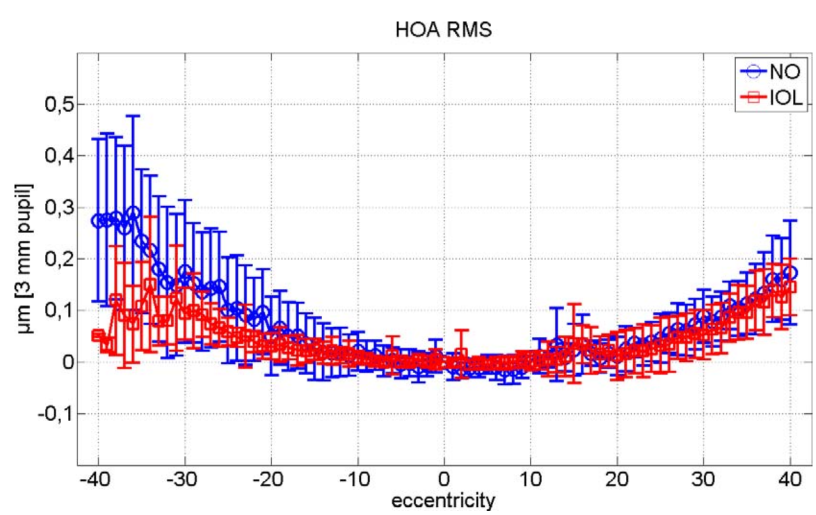

Figure 4. Mean and SD of the RMS of the HOA RMS for the healthy (NO) and the operated eye (IOL).

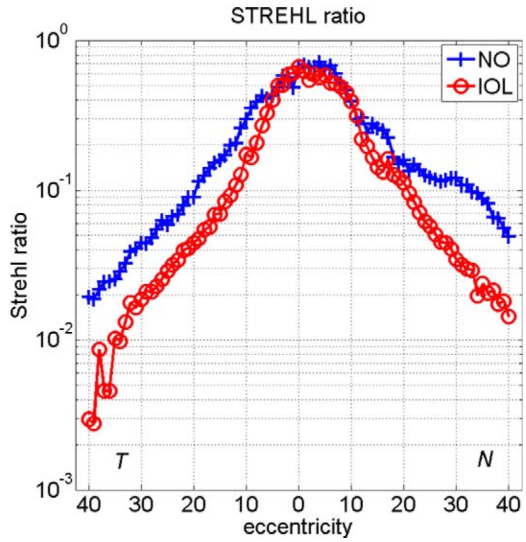

FIGURE 5. Average Strehl ratio as a function of visual angle for healthy elderly eyes (NO) and pseudophakic eyes (IOL).

with IOL was significantly (from 10° temporal retina, 20° nasal retina) worse than that of a healthy elderly eye.

As examples, the retinal images of a letter E (30 minutes of arc) at different eccentricities are shown in Figure 6. They were calculated as the convolution of the PSF with the original letter E.[20] The images were created from the aberrations of one subject but are representative for all subjects.

DISCUSSION

Since it is known that peripheral refraction can vary from subject to subject, the left and right eyes of the same subject were compared assuming mirror symmetry between both eyes. Although it may be some individual differences, a high correlation has been found before in literature[21,22] for the relative peripheral refraction and astigmatism between the two eyes. This allows us to have a direct comparison of the natural lens and the IOL in the somehow similar eyes of each subject.

For the fovea, a larger amount of higher order aberrations compared with the healthy young eye was found, as has been reported earlier.[12] However, the comparison between the operated and the nonoperated eye did not show significant differences.

The optical properties of the crystalline lens may have some effect to improve peripheral optics. Based in optical calculations, it was suggested[16] that a pseudophakic eye would have a higher amount of peripheral power errors and astigmatism. Our measurements are in agreement with this theoretical prediction: a larger amount of peripheral astigmatism was observed in all subjects independently of the power or the brand of the IOL. The source of the increase of astigmatism in an eye implanted with an IOL can be the lack of a gradient refractive index lens as the human crystalline lens. To test this hypothesis, ray-tracing simulations were conducted using ZEMAX optical analysis and design software (Zemax Development Corporation, Bellevue, WA). To represent the healthy eye, the Liou and Brennan model eye[23] was chosen. The impact of the gradient index in the lens was tested by comparing the results of this model eye with those when the gradient index lens was changed by a uniform index lens. All

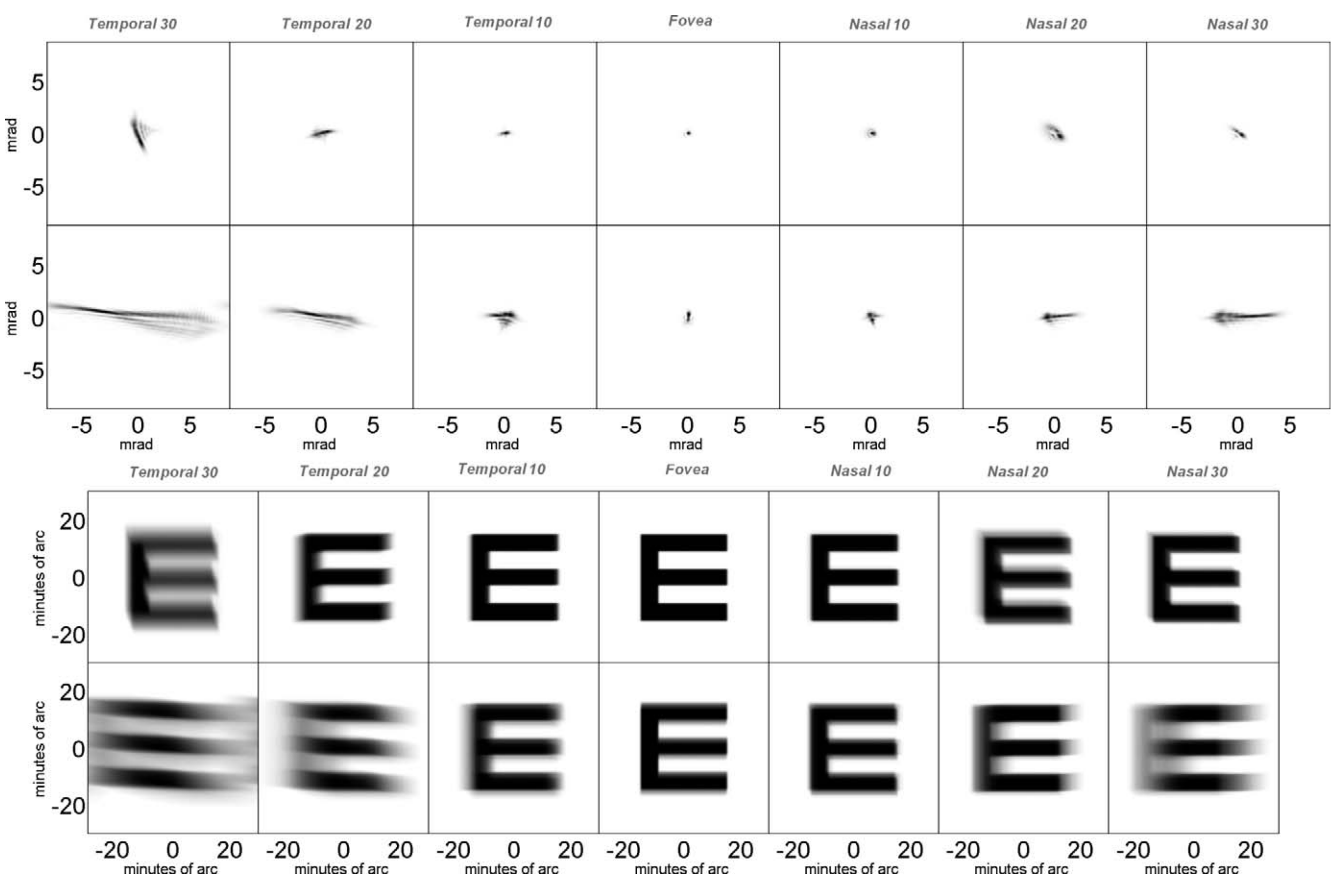

FIGURE 6. Simulation of retinal images ([*top*] PSF, [*bottom*] convolution with letter E [size 30′ arc]) for the nonoperated eye of one of the subjects, which is representative for the measured population.

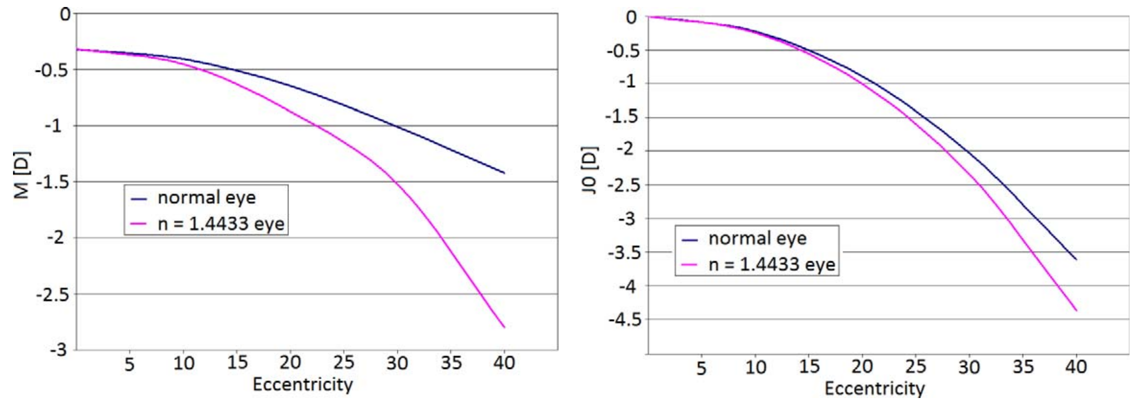

FIGURE 7. Variation of M (*left*) and J0 (*right*) as a function of eccentricity for a healthy eye and an eye with a crystalline lens with a uniform refractive index modeled as described in the text.

dimensions were kept unchanged, with only the refractive index of the lens adjusted to maintain the central refraction of the model eye. This was achieved with a refractive index of 1.4433. The impact of the gradient index of the lens on M and J0 is shown in Figure 7. The trends found in the simulations are similar to those observed in our experimental measurements, although for J0, there is a slight overestimation compared with the measured results. This can be due to the way of simulating the gradient index.[24] For these simulations, a quadratic decrease of refractive index from the center to the edge was used.

An interesting issue is the possibility of designing new IOLs to improve peripheral optics. One obvious option could be to mimic the natural lens with a gradient index design. Another option[16] is changing the shape factor of the IOL when it is positioned away from the iris. This is similar to an IOL designed to compensate for corneal coma[25] in the fovea. Other alternatives or combinations should be investigated in the future.

However, there is a critical question that also should be addressed. How is visual perception in patients affected by this reduction in peripheral image quality? It is already known that the correction of peripheral refractive errors affects some visual tasks, in particular recognition.[5] However, small changes in peripheral visual acuity were found in a study using an adaptive optics-based instrument[26] in young subjects. It can be hypothesized that patients with IOLs could do worse in tasks where peripheral vision is important as, for example, detection and scene interpretation. This could lead to a higher risk for accidents due to misinterpretation of a scene or due to missing details while moving. Another relevant aspect can be the impact of peripheral optics in visual crowding, the inability to recognize objects at different parts of the visual field.[27] Further specific visual tests will be necessary to fully determine if indeed a degradation of peripheral image quality in pseudophakic patients may have an impact on their daily visual performance.

CONCLUSIONS

We compared the peripheral image quality of pseudophakic eyes with healthy elderly eyes. The comparison was carried out patient by patient, with one eye operated with a standard monofocal IOL and the other still with the natural crystalline lens. The peripheral refraction and aberrations were measured with a high angular resolution resulting in the description of the full wavefront aberration at each degree of visual angle across the central 80° of the visual field. A decrease of the peripheral image quality was observed in the pseudophakic eye as compared with the contralateral eye. This decrease is mainly caused by an increase of astigmatism with the IOLs. This could have a negative impact on the performance of postoperative patients in visual tasks in which peripheral vision is important, as compared with individuals with healthy elderly vision. Although further research would be needed, these results may suggest the potential of improved IOLs with wide-angle designs controlling the induced peripheral astigmatism.

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