Relation between Uncorrected Astigmatism and Visual Acuity in Pseudophakia

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ABSTRACT

Purpose. The end point of astigmatic correction after cataract surgery will depend on how uncorrected astigmatism impacts distance and near vision of pseudophakic eyes. This study determined the impact of induced astigmatism and pupil size on the distance and near acuity of otherwise emmetropic pseudophakic eyes implanted with monofocal intraocular lenses.

Methods. Monocular high-contrast distance (4 m) and near (40 cm) logMAR acuity was determined in 15 subjects (mean ± 1 SD, 57.9 ± 9.0 years) without astigmatism and with 2.5 diopters (D) myopic to 2.0 D hyperopic astigmatic lenses induced in 0.5-D steps at 0-, 45-, 90-, and 135-degree axes. This experiment was repeated for the same range of induced astigmatism with 1.5-, 3-, and 6-mm artificial pupil diameters placed before one eye of 10 subjects dilated with 10% phenylephrine HCl.

Results. Distance acuity deteriorated with astigmatism for all axes tested (p < 0.01). Near acuity deteriorated with hyperopic astigmatism (p < 0.1), whereas it improved with up to 1 D of myopic astigmatism before saturating for all axes tested (p < 0.01). Distance and near acuity improved with a reduction in pupil diameter (p < 0.01). The change in distance and near acuity with induced astigmatism was smaller for 1.5-mm than for 3-mm and 6-mm pupil diameters (p < 0.01).

Conclusions. Partial restoration of near acuity with uncorrected myopic astigmatism comes with a proportional loss of distance acuity in pseudophakic eyes. Uncorrected myopic astigmatism more than 1 D results in a large loss of distance acuity at no additional benefit to near acuity. Both distance and near acuities with and without astigmatism are benefited with a reduction in pupil diameter. Uncorrected hyperopic astigmatism results in deterioration of both distance and near acuities of pseudophakic eyes.

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Advances in cataract surgery and intraocular lens (IOL) technology allow greater control over the patient’s postoperative refractive outcome and visual resolution. For monofocal IOLs, the kind that is most commonly implanted after cataract surgery, full correction of distance spherocylindrical refractive error remains the end point for many clinicians.1–3 Near vision is managed through optical aids like bifocals. However, bifocal spherocylindrical lenses that are customized for each individual may not be readily available and could be relatively expensive in several developing countries, making them an unattractive option for the lower socioeconomic section of the society.4–6 An alternate, cost-effective, and easily available option that simultaneously optimizes distance and near vision of pseudophakes is therefore necessary.

Leaving myopic astigmatism uncorrected after cataract surgery has been suggested as an option for improving the unaided near acuity of pseudophakes implanted with monofocal IOLs.7–15 This option is attractive in that relatively inexpensive “off-the-shelf” single-vision spherical lenses could be prescribed to correct distance vision and the astigmatism that is left uncorrected could provide useful near vision. However, previous studies that have considered this option have not determined the relative impact of uncorrected astigmatism on distance acuity.7–15 It therefore remains unclear whether this strategy can simultaneously optimize distance and near vision of pseudophakic eyes. The impact of astigmatic axis and the interaction between pupil size and uncorrected astigmatism on the distance and near acuities also remain uncertain.11–13 Overall, questions of fundamental clinical importance related to the impact of uncorrected astigmatism on distance and near acuity of pseudophakes have not been answered satisfactorily. These include does uncorrected myopic astigmatism improve near acuity of
pseudophakes, and, if so, what magnitude should be left uncorrected and at what axis? In doing so, how much compromise in distance acuity is to be expected? What role do the pupils play in determining acuity with uncorrected astigmatism? Two experiments were conducted here to address these questions comprehensively.

Changes in distance and near acuities with uncorrected astigmatism could be inferred from the changes in the magnitude of blur resulting from the focal planes not converging onto the retina (Fig. 1A, B). The magnitude of blur could be quantified using a blur strength metric, defined as:

\[ B = \sqrt{M^2 + J_0^2 + J_{45}^2} \]  

where \( B \) is the blur strength and \( M, J_0, \) and \( J_{45} \) are the dioptric power vector equivalents of the spherical equivalent of refraction (i.e., sphere + cylinder/2), horizontal/vertical astigmatism, and oblique astigmatism, respectively. For an emmetropic pseudophakic eye, the spherical blur experienced at distance is 0 D and at near (40 cm) is 2.5 D hyperopia. Accordingly, the blur strength for distance and near without astigmatism is 0 and 2.5 D, respectively. For distance, the blur strength increases monotonically with increasing magnitudes of myopic and hyperopic astigmatism at all axes (Fig. 1C). For near, the blur strength decreases progressively up to 2.5 D of myopic astigmatism because of an overall reduction in the magnitude of hyperopic blur, whereas it increases with increasing magnitudes of hyperopic astigmatism because of an increase in the magnitude of hyperopic blur for all axes tested (Fig. 1D). It is therefore hypothesized that monocular distance acuity of pseudophakes will deteriorate with increasing magnitudes of uncorrected myopic and hyperopic astigmatism. Near acuity, on the other hand, will improve with uncorrected myopic astigmatism, and it will deteriorate with uncorrected hyperopic astigmatism.

METHODS

Fifteen unilateral pseudophakes (mean ± 1 SD age, 57.9 ± 9.0 years) with no reported ocular or medical history were recruited for this prospective study from the L. V. Prasad Eye Institute, Hyderabad, India. The study adhered to the tenets of the Declaration of Helsinki, and it commenced after the subjects provided written informed consent duly approved by the local institutional review board. All subjects had undergone uncomplicated
cataract surgery at least 5 weeks before the study, and the acrylic foldable monofocal IOL (Acrysof, Alcon) was positioned appropriately in the lens bag. All subjects were emmetropic (determined through objective and subjective refraction), with uncorrected distance acuity better than or equal to 20/20 and best-corrected near acuity (with 2.5 D near addition) better than or equal to N6 (or ~20/32) at 40 cm. Numerous subjects were screened, and only those who strictly met the inclusion criteria were enrolled.

Experiment 1 determined the impact of magnitude and axis of induced astigmatism on monocular distance (4 m) and near (40 cm) logMAR acuity of pseudophakes. The induced astigmatism paradigm allowed the impact of a given magnitude and axis of astigmatism on acuity to be studied systematically, without influence of confounding factors that may be present in subjects with habitual astigmatism (e.g., adaptation to astigmatic blur). Acuities were measured without astigmatism and with 2.5 D myopic to 2.0 D hyperopic astigmatism, induced in 0.5-D steps, along 0-, 45-, 90-, and 135-degree axes. Astigmatic lenses were placed before the pseudophakic eye on a trial frame at 14-mm vertex distance while the fellow eye was occluded. Distance acuity was determined on a letter-by-letter basis (0.02 logMAR units allotted per letter) for each combination of lens power and axis using English optotype charts. Near acuity was recorded using English word charts as the smallest line in chart that was read correctly at least halfway through. No near-addition lenses were worn by subjects while measuring near acuity. Three different acuity charts with varying combinations of optotypes were used in each subject to avoid memorization of the letter sequence. The order of lens power and axis was also randomized for each subject, such that the smallest acuity line read was different for each lens combination. The effective powers at the corneal plane of the largest cylindrical lenses used in this study (+2.5 and −2.0 D) differed from their expected value by only 0.2 D, and this difference was considered insignificant.

In experiment 1, near acuity was measured using a word reading task, whereas distance acuity was measured using an optotype recognition task. To determine if the near acuity of pseudophakic eyes with uncorrected astigmatism depended on the nature of near

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**FIGURE 2.**
Mean (±1 SEM) distance (A) and near (B) logMAR acuity plotted as a function of the magnitude of induced myopic and hyperopic astigmatisms for all axes tested. Mean (±1 SEM) near logMAR acuity without astigmatism and with 1 and 2 D of induced myopic astigmatism recorded for the word reading and optotype recognition tasks (C). Scatter diagram of blur strength (BS) plotted against logMAR acuity for all subjects in experiment 1 (D).
RESULTS

The mean (±1 SEM) distance logMAR acuity without astigmatism in experiment 1 was $-0.06 ± 0.08$, and it decreased monotonically with increasing magnitudes of induced myopic and hyperopic astigmatism for all four axes tested (Fig. 2A). Two-factor analysis of variance (ANOVA) showed that the magnitude of astigmatism had significant effects on distance acuity ($F_{595, 9} = 172.6; p < 0.001$), whereas the axis ($F_{595, 3} = 0.75; p = 0.52$) and the interaction between magnitude and axis ($F_{595, 27} = 0.54; p = 0.97$) were not significant. Post hoc Games-Howell test showed that the distance acuity without astigmatism was significantly different from those obtained with all magnitudes of induced astigmatism ($p < 0.001$), except with 0.5 D of induced hyperopic astigmatism ($p = 0.93$).

The deterioration in distance acuity was greater with induced myopic than with induced hyperopic astigmatism, with the rate of change in acuity being $0.31 \text{logMAR per diopter of astigmatism in the former and 0.23 logMAR per diopter of astigmatism in the latter } (r^2 \geq 0.97 \text{ for both}; p < 0.001) \text{ (Fig. 2A). The } y \text{ intercept for both regression equations was } -0.13 \text{logMAR, and it corresponded well to the distance acuity obtained without astigmatism (Fig. 2A).}$

The mean (±1 SEM) near logMAR acuity in experiment 1 was $0.6 ± 0.15$ without astigmatism. Two-factor ANOVA showed that astigmatic magnitude had a significant effect on near acuity ($F_{595, 9} = 57.5; p < 0.001$), whereas axis ($F_{595, 3} = 0.53; p = 0.66$) and the interaction between magnitude and axis were not significant ($F_{595, 27} = 0.18; p > 0.9$). Post hoc test showed that near acuity with all magnitudes of induced myopic astigmatism (except 0.5 D) was significantly better than the acuity without astigmatism ($p < 0.001$). Near acuities with 0.5 and 1.0 D of induced myopic astigmatism were significantly different from each other ($p = 0.01$), beyond which they were not statistically significant ($p > 0.9$). Near acuity deteriorated slightly with induced hyperopic astigmatism, and this deterioration was significant only for 2 D of hyperopic astigmatism ($p < 0.001$).

Figure 2C plots histograms of the mean (±1 SEM) near logMAR acuity obtained for the word reading and optotype recognition tasks. Data from all axes were pooled together in this analysis. Two-factor ANOVA (astigmatic magnitude × reading task) showed a statistically significant main effect of astigmatism magnitude on the near acuity ($F_{75, 2} = 67.9; p < 0.001$), with post hoc Games-Howell test showing near acuity with +1 D (words, $0.25 ± 0.01$; optotypes, $0.26 ± 0.02$) and +2 D (words, $0.16 ± 0.01$; optotypes, $0.14 ± 0.01$) induced astigmatism to be statistically significantly different from each other ($p < 0.001$) and from the habitual viewing condition (words, $0.38 ± 0.02$; optotypes, $0.40 ± 0.03$) ($p < 0.001$ for both). The main effect of reading task and the interaction between astigmatism magnitude and reading task were not statistically significant ($p > 0.9$). The nature of near task therefore did not play a crucial role in determining the near acuity of pseudophakes with induced astigmatism (Fig. 2C).

Data analyses were performed using Microsoft Excel, SPSS, and Matlab. Unless indicated otherwise, a negative cylinder format is used to denote astigmatism throughout this study. Positive sign denotes induced myopic astigmatism, and negative sign denotes induced hyperopic astigmatism in this study (Figs. 1C, D; 2A, B; 3A, B).

FIGURE 3.

Mean (±1 SEM) distance (A) and near (B) logMAR acuity plotted as a function of the magnitude of induced myopic and hyperopic astigmatisms for 1.5-, 3.0-, and 6.0-mm diameter pupils.
The changes in distance and near acuities with induced astigmatism were also qualitatively similar and well correlated with the corresponding changes in blur strength ($r = 0.93$) (Fig. 2D).

To determine the relation between the loss of distance acuity and the gain in near acuity with induced myopic astigmatism, the change in near acuity with 1 and 2 D of myopic astigmatism at all axes tested (relative to the no astigmatism condition) was plotted against the corresponding change in distance acuity for each subject (Fig. 4). Positive values of $x$ and $y$ axes in this figure indicated an improvement in acuity with induced astigmatism. Distance acuity deteriorated, and the corresponding near acuity improved with induced myopic astigmatism relative to no astigmatism (Fig. 4). Most data points with 2 D of induced myopic astigmatism were more negative than the 1-D data points, indicating that the former resulted in greater loss of distance acuity than the latter, with no further improvement in near acuity (Fig. 4). The change in distance and near acuities with induced myopic astigmatism was poorly correlated to each other, suggesting that the loss in distance acuity cannot be easily predicted from the gain in near acuity ($r \leq 0.25$; $p \geq 0.66$).

A reduction in pupil diameter had an overall beneficial effect on distance and near logMAR acuity with and without induced astigmatism (Fig. 3). The distance acuity loss with induced astigmatism was least with the 1.5-mm pupil diameter, followed by the 3.0- and 6.0-mm pupil diameters (Fig. 3A). Two-factor ANOVA showed a statistically significant main effect of pupil diameter ($F_{135, 2} = 47.6; p < 0.001$) and astigmatism magnitude ($F_{135, 4} = 55.2; p < 0.001$) on distance acuity of pseudophakes (Fig. 3A). Post hoc Games-Howell test showed that distance acuities for all three pupil diameters were significantly different from each other ($p < 0.01$). The distance acuities for all magnitudes of astigmatism were also significantly different from each other ($p < 0.01$). The interaction between pupil diameter and astigmatism magnitude was statistically significant ($F_{135, 8} = 1.32; p = 0.009$), indicating that the changes in distance acuity with induced astigmatism depended on the pupil diameter.

Near acuity also changed significantly with pupil diameter ($F_{135, 2} = 44.1; p < 0.001$) and astigmatism magnitude ($F_{135, 4} = 57.2; p < 0.001$) (Fig. 3B). Post hoc Games-Howell test showed that near acuities for all three pupil diameters were significantly different from each other ($p < 0.01$). The near acuities for all magnitudes of astigmatism (except between 1 and 2 D of myopic astigmatism) were significantly different from each other ($p < 0.01$). The interaction between pupil diameter and astigmatism was not statistically significant ($F_{135, 8} = 0.32; p = 0.23$), indicating that the magnitude of near acuity change with induced astigmatism was independent of pupil diameter.

**DISCUSSION**

This study determined the impact of uncorrected astigmatism on monocular distance and near logMAR acuity of pseudophakes with monofocal IOL implants. This was achieved by inducing astigmatic errors of various magnitudes and axes before one eye of otherwise emmetropic pseudophakes. The key findings of this study are as follows:

1) Distance acuity deteriorated significantly with increasing magnitudes of induced astigmatism for all axes tested (Fig. 2A). The loss in distance acuity was greater for induced myopic astigmatism than for induced hyperopic astigmatism (Figs. 2A).

2) Near acuity was relatively poor without astigmatism, and it improved with up to 1 D of induced myopic astigmatism before saturating for all axes tested (Fig. 2B). Near acuity deteriorated with induced hyperopic astigmatism for all axes tested (Fig. 2B).

**FIGURE 4.**

Change in near logMAR acuity with 1 and 2 D of induced myopic astigmatism plotted against the corresponding change in distance logMAR acuity, both relative to the no astigmatism condition.
3) The deterioration in distance acuity with induced astigmatism was lesser for smaller pupils (Fig. 3A). The corresponding improvement in near acuity with induced myopic astigmatism was similar for all pupil diameters (Fig. 3A).

4) The empirical trends in acuity were qualitatively similar and well correlated to the changes in magnitude of blur experienced by the pseudophakic eye (Figs. 1C, D; 2D).

These results have important implications for the management of astigmatism in pseudophakic eyes. It is apparent that uncorrected myopic astigmatism has a beneficial effect on monocular near acuity of pseudophakes implanted with monofocal IOL (Figs. 2–4). Near acuity improves from about 0.6 logMAR units without astigmatism to about 0.4 logMAR units with 1 D of induced myopic astigmatism, beyond which near acuity leveled off (Fig. 2B). The latter acuity roughly corresponds to the size of a newspaper print, suggesting that pseudophakes may be able to perform their routine near tasks with this magnitude of uncorrected myopic astigmatism. The restoration of near vision with induced myopic astigmatism is however only partial, as indicated by the fact that the best-corrected near acuity of all participants was better than or equal to 0 logMAR units. Tasks requiring very fine near acuity may therefore require additional near-vision correction.

The strategy of leaving myopic astigmatism uncorrected for restoring near vision of pseudophakes must be considered in the context of the associated loss in distance acuity. Indeed, distance acuity deteriorated monotonically with increasing myopic astigmatism even while near acuity leveled off beyond 1 D of myopic astigmatism (Figs. 2–4). Therefore, while uncorrected myopic astigmatism may be considered as a strategy for optimizing distance and near vision of pseudophakes, only up to 1 D of myopic astigmatism may be left uncorrected to partially restore near vision, without introducing a large compromise in distance vision. Beyond this magnitude, the visual experience of pseudophakic eyes may be suboptimal because of a large loss in distance acuity, at no additional benefit to near acuity. Residual hyperopic astigmatism must be fully corrected in pseudophakic eyes to avoid deterioration of distance and near vision (Figs. 2, 3).

The changes in distance and near acuity with induced astigmatism can be readily explained from the underlying changes in the magnitude of blur strength (Fig. 1). Notably, the improvement in near acuity with induced myopic astigmatism (or plus cylindrical lenses) is caused by the overall reduction in the magnitude of hyperopic blur induced by the shift in the location of one of the focal planes toward the retina and may not necessarily be caused by the meridional blur induced by uncorrected myopic astigmatism. Conversely, the worsening of near acuity with induced hyperopic astigmatism (or negative cylindrical lenses) is caused by an increase in the magnitude of hyperopic blur induced by the shift in one of the focal planes away from the retina. Similar logic can be applied to explain the loss in distance acuity with both induced myopic and hyperopic astigmatisms.

Changes in distance and near acuity were similar for all four axes of induced astigmatism, suggesting that the axis of uncorrected astigmatism has no bearing on the visual experience as long as the magnitude of astigmatism is optimized (Fig. 2). This result is similar to that observed by Remon et al. for five different axes of induced myopic astigmatism in young phakic eyes. However, this result differs from those of studies that report better near acuity in pseudophakes with uncorrected against-the-rule myopic astigmatism than with uncorrected-with-the-rule myopic astigmatism. The difference in results may arise from the fact that earlier studies determined near acuity with habitual uncorrected astigmatism, whereas the current study determined near acuity with induced astigmatism. Adaptation to astigmatic blur is orientation dependent, and, perhaps, pseudophakes in the former group adapted to against-the-rule astigmatic blur more than to with-the-rule astigmatic blur. Although short-term adaptation to astigmatic blur has been reported previously, it seems unlikely in this study because the magnitude, axis, and polarity of astigmatic blur varied continuously and randomly during the experimental period.

A reduction in pupil diameter had a significant beneficial impact on the distance and near acuity of pseudophakes without astigmatism (Fig. 3). Although not measured, reduced pupil diameter may also have resulted in better habitual near acuity for subjects who participated in the control experiment (~0.4 logMAR units) than those of the entire cohort (~0.6 logMAR units) (compare Fig. 2B, C). The magnitude of deterioration in distance acuity with induced astigmatism was lesser for smaller pupil diameters, whereas the corresponding improvement in near acuity was about the same for all pupil diameters (Fig. 3). These results suggest that pupillary miosis would supplement the beneficial impact of uncorrected myopic astigmatism in improving near vision of pseudophakic eyes. Overall, these results are completely predicted from the reduction in size of the blur patch and widening of depth of focus that occurs with a reduction in pupil diameter.

Induced myopic astigmatism resulted in greater loss of distance acuity than induced hyperopic astigmatism (Fig. 2A). This is similar to the observations of Ravikumar et al., Ohlendorf et al., and Atchison and Mathur on young phakic eyes. This difference may be caused by variations in the accommodative state of the eye with induced astigmatism—eyes with hyperopic astigmatism could accommodate to place the circle of least confusion on the retina, thereby experiencing slightly better acuity than eyes with myopic astigmatism. The current study in pseudophakes however suggests only a minimal role of accommodation in causing this difference. The typical anterior movement of a monofocal IOL to increase optical power during attempted accommodation (~0.05 mm) seems too small to account for the observed differences in acuity (1.0 mm anterior movement of a 20-D IOL in an eye with 24-mm axial length generates a power change of about 1.3 D). Alternately, the observed difference in distance acuity could arise from the way myopic and hyperopic astigmatisms interact with the eye’s higher order optical aberrations or be caused by differences in phase shifts induced in the retinal image with astigmatic blur. Further experiments are required to address these possibilities in detail.

**CONCLUSIONS**

Monocular near logMAR acuity of pseudophakes improves with up to 1 D of uncorrected myopic astigmatism but only with a proportional loss in distance acuity. The visual experience may be suboptimal beyond this magnitude because of a large loss of distance acuity at no additional benefit to near vision. Leaving
myopic astigmatism uncorrected for optimizing near vision of pseudophakic eyes must therefore be considered in the context of the associated loss in distance vision. The beneficial effect of uncorrected myopic astigmatism may be further supplemented in pseudophakic eyes with smaller pupil diameters. Both distance and near acuity deteriorate with uncorrected hyperopic astigmatism, and it should be fully corrected after cataract surgery.

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