The Effect of Decentration on Higher-Order Aberrations

Precisely placing aspheric IOLs is important for improving patients' visual quality.

BY EDWIN J. SARVER, PHD; LI WANG, MD, PHD; AND DOUGLAS D. KOCH, MD

The average human cornea contains a certain amount of positive spherical aberration.[1,2] Because spherical IOLs also have positive spherical aberration, implanting them in the eye increases the degree of this higher-order aberration in the optical system. This fact suggests that implanting IOLs with one or more negatively aspheric surfaces (aspheric IOLs)[3-8] will benefit patients by neutralizing the natural spherical aberrations of their corneas. At minimum, aspheric IOLs should not induce additional positive spherical aberration. The decentration of an implanted aspheric IOL, however, may overshadow the lens' apparent benefits by inducing coma or reducing modulation transfer.[1,3,9]

TABLE 1. CORNEAL SHAPES OPTIMIZED FOR MODEL IOLS WITH NEGATIVE, ZERO, AND POSITIVE SPHERICAL ABERRATION

Model Cornea	Optimized for IOL	Corneal K-Value	Spherical Aberration (µm)
Cornea with negative spherical aberration	IOL with positive spherical aberration	-0.967061	-0.2374
Cornea with zero spherical aberration	IOL with zero spherical aberration	-0.632661	-0.0446
Cornea with positive spherical aberration	IOL with negative spherical aberration	-0.140545	0.2701

TABLE 2. SPHERICAL ABERRATIONS INDUCED IN MODEL CORNEAS BY DECENTERED IOLS

Model Cornea	IOL With Positive Spherical Aberration			IOL With Zero Spherical Aberration			IOL With Negative Spherical Aberration		
	Decentration (mm)			Decentration (mm)			Decentration (mm)		
	Zero	0.5	1.0	Zero	0.5	1.0	Zero	0.5	1.0
Cornea with negative spherical aberration	0.0001µm	0.0032µm	0.0131µm	-0.0941µm	-0.0933µm	-0.0910µm	-0.2462µm	-0.2496µm	-0.2602µm
Cornea with zero spherical aberration	0.0934µm	0.0965µm	0.1061µm	Zero	0.0008µm	0.0031µm	-0.1503µm	-0.1536µm	-0.1636µm
Cornea with positive spherical aberration	0.2400µm	0.2429µm	0.2522µm	0.1477µm	0.1485µm	0.1508µm	Zero	-0.0030µm	-0.0120µm

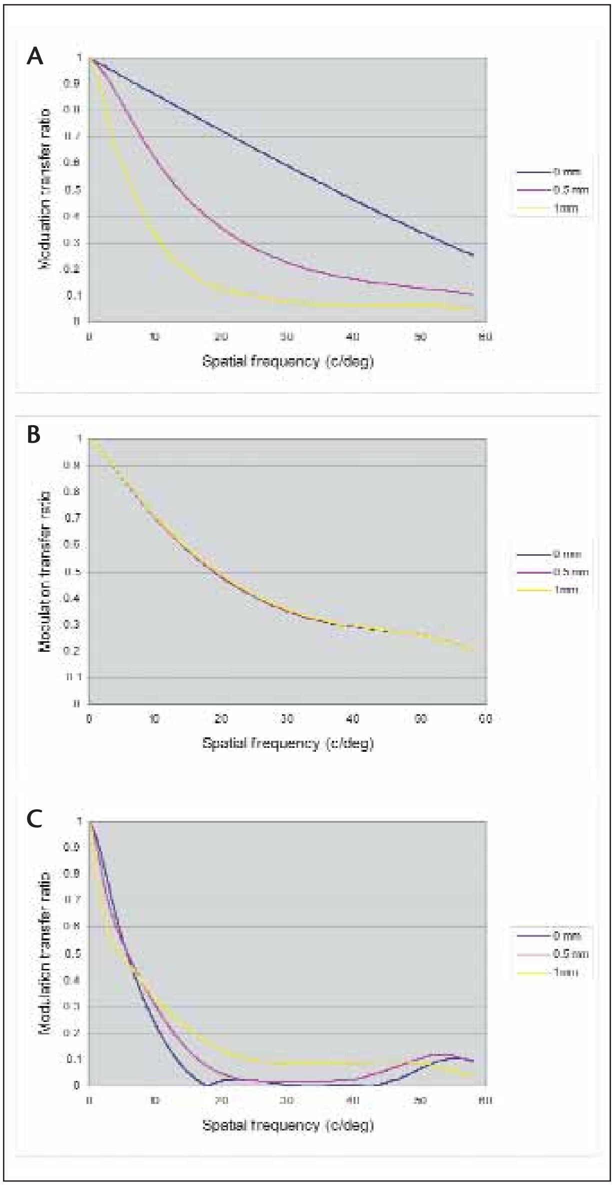

Figure 1. These graphs show the modulation transfer functions for the Soflex spherical IOL (A), the Sofport AO aspheric IOL (B), and the Tecnis aspheric IOL (C) imposed on a cornea with negative spherical aberration. Each IOL is decentered by zero, 0.5, and 1.0mm.

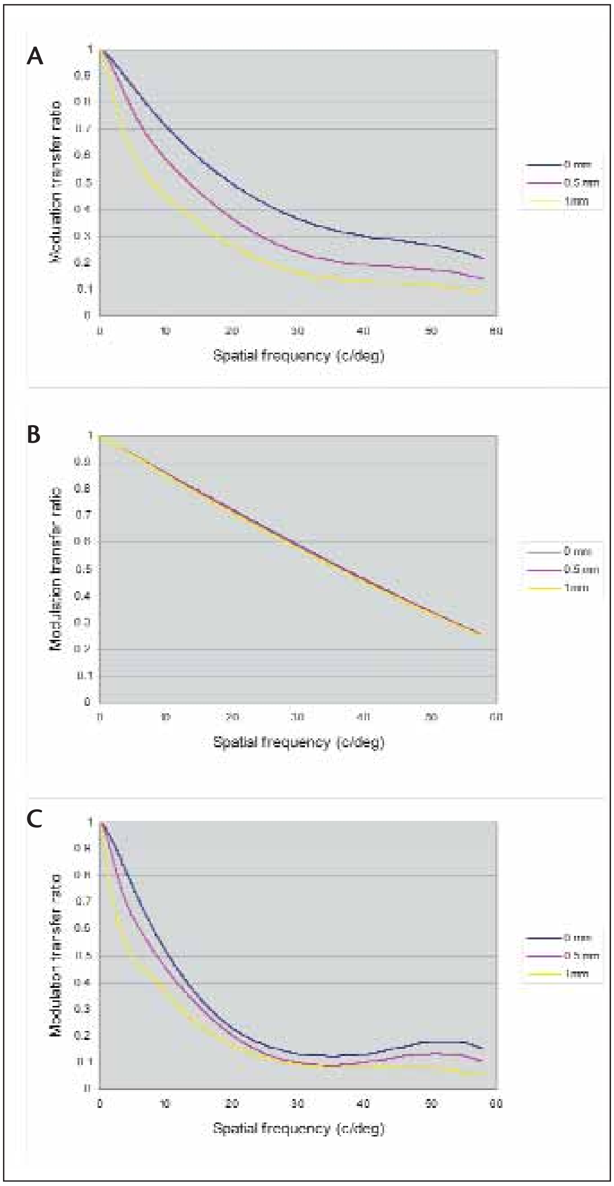

Figure 2. These graphs show the modulation transfer functions for the Soflex spherical IOL (A), the Sofport AO aspheric IOL (B), and the Tecnis aspheric IOL (C) imposed on a cornea with zero spherical aberration. Each IOL is decentered by zero, 0.5, and 1.0mm.

This article presents the results of a study in which we measured the effect of decentration on the performance of aspheric IOLs.

METHOD

We used a commercial optical engineering program from Zemax Development Corporation (Bellevue, WA) to perform optical ray tracing and analysis of aspheric schematic eye models and IOL models based on the parameters described by Altmann et al.[3]

The schematic eye model was fixed to 5mm, which is the midrange of the pupil's diameter for 60-year-old subjects over various lighting conditions. The 22.00D IOL models had positive, negative, and zero spherical aberration, and the decentration values used in the study were zero (on axis), 0.5, and 1.0mm.

THE TILT AND DECENTRATION OF ASPHERIC IOLs: WHAT ARE THE LIMITS OF TOLERANCE?

By Mark Packer, MD; I. Howard Fine, MD; and Richard S. Hoffman, MD

The eye model used for the design of the negatively aspheric Tecnis IOL (Advanced Medical Optics, Inc., Santa Ana, CA) assumed a rotationally symmetric cornea reflecting the mean spherical aberration in a population of patients presenting for cataract surgery. This model also assumed monochromatic light and a symmetric cornea. Critics suggested that the model oversimplified the actual effects of the wavefront-corrected IOL by ignoring the contributions of polychromatic light as well as the implications of asymmetric corneal aberrations such as coma.[1]

An eye model employing monochromatic, symmetric optics does suggest tight tolerances for the tilt and decentration of IOLs that correct spherical aberration. For example, the model eye used in the Tecnis IOL's design study demonstrates a tolerance of 0.4mm of decentration and 7° of tilt for the modified prolate IOL with Z(4,0) = -0.27µm. At this degree of decentration or tilt, the contrast ratio of 15 cycles per degree for the lens becomes equivalent to that of a standard spherical IOL.

AN EXPLANATION

The reason that decentration reduces the optical efficiency of an aspheric lens may be explained by the induction of higher-order aberrations such as coma.[2] As an example, one might consider an aspheric IOL decentered 0.5mm along the 180° meridian for a 6-mm pupil. Given a coefficient of fourth-order spherical aberration in the IOL of -0.29µm, the coefficient of induced third-order horizontal coma would be -0.30µm.

STUDYING THE MATTER

The goal of a meta-analysis of the peer-reviewed literature on the subject of IOLs' tilt and decentration was to determine the approximate percentage of pseudophakic eyes that one might expect to reside within the tolerances set by the aforementioned eye model.[3] The selected studies required a complete, continuous curvilinear capsulorhexis and in-the-bag IOL fixation. The postoperative measurement of the IOLs' positions was assessed using Scheimpflug photography, which measures along the visual axis. Analyzing the means and standard deviations of the IOLs' decentration and tilt showed a wide range of outcomes, depending on the lenses' materials and designs.

When asymmetric aberrations and polychromatic light are taken into account, however, a newly developed model suggests greatly relaxed tolerances for the tilt and decentration of wavefront-corrected IOLs. This model was developed using corneal wavefront data from patients who presented for cataract surgery, including both symmetric and asymmetric aberrations, and was subsequently verified with these patients' clinical postoperative data.[1] In the verification study, three surgeons randomly assigned a wavefront-corrected IOL to one eye and a standard spherical IOL to the fellow eye of 79 patients. The Zernike terms predicted by the model for both the wavefront-corrected and the control IOL closely approximated the clinical results. In particular, this model very closely predicted the Z(4,0) term for both the wavefront-corrected and the control IOL.

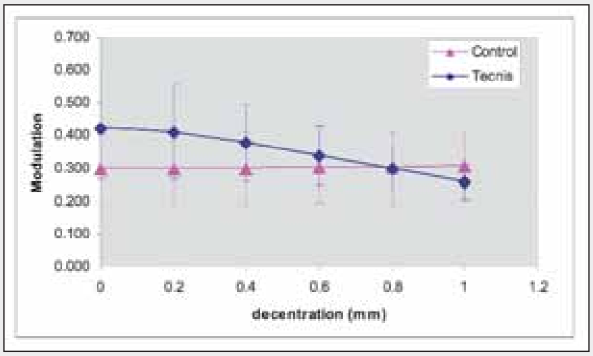

Figure 1. This graph shows the average, radial modulation transfer function versus decentration. As the optical center of the IOL moves farther from the visual axis, the efficiency of light's transmission decreases.

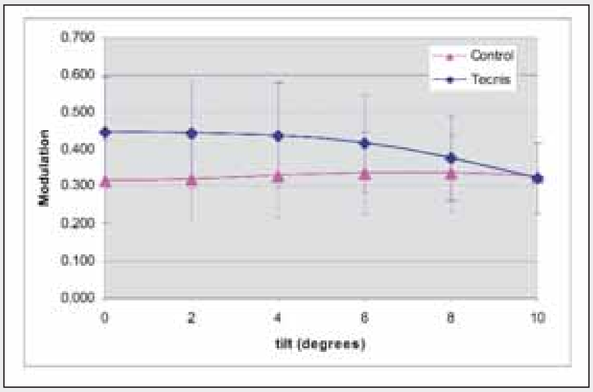

Figure 2. This graph shows the average, radial modulation transfer function versus tilt. As the lens' optic tilts with respect to a plane perpendicular to the visual axis, the efficiency of light's transmission decreases.

THE TILT AND DECENTRATION OF ASPHERIC IOLs: WHAT ARE THE LIMITS OF TOLERANCE? (*CONT.*)

The validated eye model was then used to evaluate the effects of decentration and tilt on the modulation transfer function of the wavefront-corrected IOL. Assuming polychromatic illumination and incorporating the effects of the clinically validated asymmetric aberrations, the modulation transfer function's degradation with decentration to the level of a control standard spherical IOL occurred at 0.8 instead of 0.4mm, as in the simplified, symmetric eye model. The degradation of the modulation transfer function with tilt to this level occurred at 10° instead of 7° (Figures 1 and 2).

Analyzing the peer-reviewed literature on decentration in terms of a tolerance of 0.8mm, as demonstrated by the clinically verified eye model, reveals a significant reduction in the percentage of cases outside of tolerance. For example, one would expect the percentage of eyes with a three-piece silicone IOL that has PMMA haptics and is decentered greater than 0.8mm to be 0.0001% (Table 1).

CONCLUSION

If common levels of tilt and decentration significantly affected the functioning of wavefront-corrected IOLs, it would be difficult to explain the evidence of an elimination of spherical aberration and of improved functional vision found in multiple investigations of the Tecnis IOL. The new, clinically validated eye model described by Piers et al[1] helps relieve this potential paradox. Areas for future research include a direct verification of the decentration and tilt of wavefront-corrected IOLs.

TABLE 1. THE PERCENTAGE OF EYES WITH A DECENTRATION LARGER THAN 0.8MM

IOL Type	Eyes
Overall	0.06%
Optic/haptic materials	
Silicone/PMMA	0.0001%
PMMA/PVDF	4.27%
Silicone/Prolene	0.33%
PMMA one-piece	0.07%
Acrylic/PMMA	0.06%
Hydrogel/PMMA	0.0002%

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For each of the three IOL models, we determined the corneal asphericity (K-value) needed to optimize the eye model and produced three corneal shapes that matched the IOLs' apical radii of curvature. Table 1 lists the optimized corneal models and their corresponding spherical aberrations. It is unlikely that a natural cornea would have -0.2374μm^2 of spherical aberration, but the model was useful for the present analysis.

For each of the three corneal shapes, we substituted one of the IOL models (on axis) and optimized the distance to the retina for best focus. We then obtained the modulation transfer functions and Zernike aberrations for the three values of decentration using 512 X 512 rays.

RESULTS

Figures 1, 2, and 3 show the modulation transfer functions for the decentration values of zero, 0.5, and 1.0mm imposed on model corneas with negative, positive, and zero spherical aberration, respectively.

The Zernike aberrations for spherical aberration (Z[4,0]), astigmatism (Z[2,2]), and coma (Z[-1,3]) are listed in Tables 2, 3 and 4. Because the decentration of the

TABLE 3. ASTIGMATISM INDUCED BY DECENTERED IOLs									
Model Cornea	IOL With Positive Spherical Aberration			IOL With Zero Spherical Aberration			IOL With Negative Spherical Aberration		
	Decentration (mm)			Decentration (mm)			Decentration (mm)		
	Zero	0.5	1.0	Zero	0.5	1.0	Zero	0.5	1.0
Cornea with negative spherical aberration	Zero	-0.0505µm	-0.2074µm	Zero	-0.0094µm	0.0076µm	Zero	0.0998µm	0.4086µm
Cornea with zero spherical aberration	Zero	-0.0503µm	-0.2066µm	Zero	0.0021µm	0.0077µm	Zero	0.0993µm	0.4064µm
Cornea with positive spherical aberration	Zero	-0.0500µm	-0.2054µm	Zero	0.0021µm	0.0078µm	Zero	0.0985µm	0.4031µm

TABLE 4. COMA INDUCED BY DECENTERED IOLs									
Model Cornea	IOL With Positive Spherical Aberration			IOL With Zero Spherical Aberration			IOL With Negative Spherical Aberration		
	Decentration (mm)			Decentration (mm)			Decentration (mm)		
	Zero	0.5	1.0	Zero	0.5	1.0	Zero	0.5	1.0
Cornea with negative spherical aberration	Zero	-0.1459µm	-0.3028µm	Zero	-0.0094µm	-0.0210µm	Zero	0.2269µm	0.4679µm
Cornea with zero spherical aberration	Zero	-0.1451µm	-0.3012µm	Zero	-0.0096µm	-0.0214µm	Zero	0.2243µm	0.4626µm
Cornea with positive spherical aberration	Zero	-0.1439µm	-0.2988µm	Zero	-0.0099µm	-0.0220µm	Zero	0.2203µm	0.4543µm

IOLs was performed only in the y direction, the other terms for astigmatism and coma were zero.

DISCUSSION

We can make several observations about the optical performance of the IOLs as a function of the corneal shape and the amount of decentration of the IOL. Maintaining minimal decentration (less than 0.5mm) and matching the IOL to the amount of corneal spherical aberration will provide the best optical performance. For misalignments of 0.5mm or more, the IOL with zero spherical aberration (Sofport AO; Bausch & Lomb, Rochester, NY) provides better visual quality than the spherical (Soflex; Bausch & Lomb) or the aspheric (Tecnis; Advanced Medical Optics, Santa Ana, CA) IOL.

All three IOLs appear to perform about the same in terms of ocular spherical aberration as a function of decentration (Table 2). The IOLs produce approximately the same level of ocular spherical aberration in the resulting eye model when each of them is decentered. The IOL with zero spherical aberration appears to cause slightly less total ocular spherical aberration only because it is optimized for the central range of the corneas under consideration. Surprisingly, the astigmatism and coma induced due to decentration is relatively independent of the corneal shape (Tables 3 and 4). Spherical IOLs decentered by 0.5 and 1.0mm induced 14 to 25 times more coma and astigmatism than similarly decentered IOLs with zero spherical aberration. IOLs with negative spherical aberration induced even higher degrees of coma and astigmatism versus IOLs

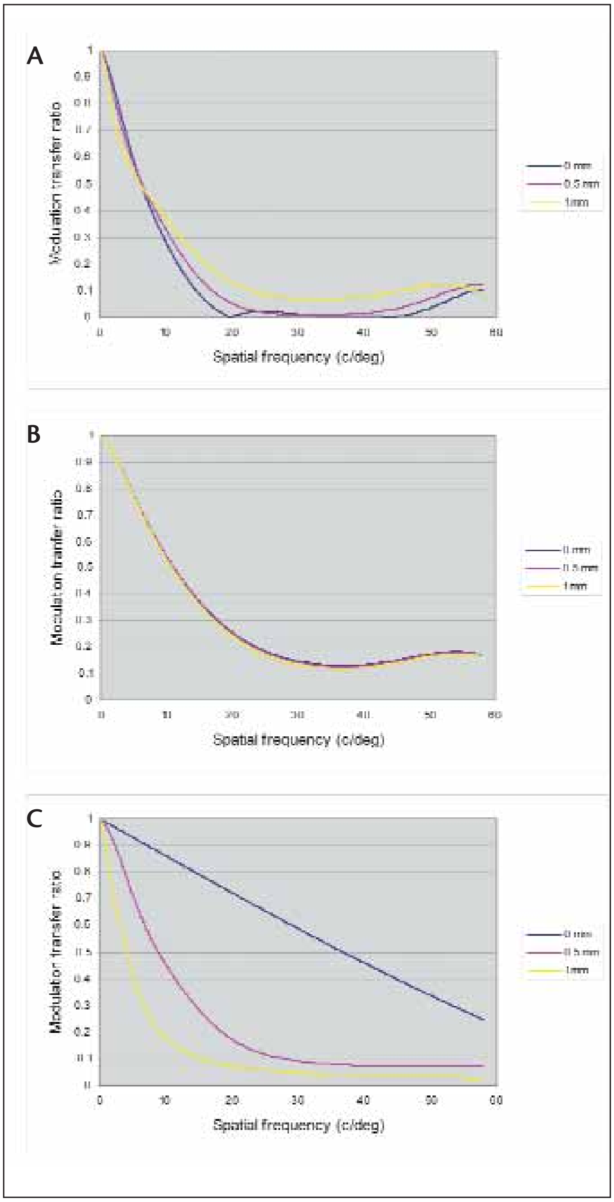

Figure 3. These graphs show the modulation transfer functions for the Soflex spherical IOL (A), the Sofport AO aspheric IOL (B), and the Tecnis aspheric IOL (C) imposed on a cornea with positive spherical aberration. Each IOL is decentered by zero, 0.5, and 1.0mm.

with zero spherical aberration (23 to 50 times as much) when both were decentered by 0.5 and 1.0mm.

Although a more thorough optical analysis of the IOLs' decentration would include the effects of tilt, defocus, and polychromatic changes, we can draw the following generalizations from our study.

First, IOLs should be selected as a function of the corneal spherical aberration and anticipated decentration for best performance. Second, the modulation transfer function of IOLs with zero spherical aberration is not affected by zero to 1.0mm of decentration. Third, the modulation transfer function of spherical and aspheric IOLs is adversely affected by 0.5 to 1.0mm of decentration. Finally, IOLs with zero spherical aberration induce less coma and astigmatism if they decenter than IOLs with positive and negative spherical aberration.

CONCLUSION

Our study shows how the decentration of an aspheric IOL causes ocular aberrations and demonstrates that the magnitude of the induced aberrations is a function of the aspheric IOL. ■

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