Objective: To predict postoperative refractive astigmatism in the second eye undergoing cataract surgery using standard biometry and information obtained from the first eye.

Methods: We conducted a retrospective study of 160 patients undergoing bilateral sequential phacoemulsification with capsular bag implantation of a hydrophobic acrylic lens at a Veterans Affairs medical center. Keratometric and refractive astigmatism were described by Jackson cross cylinder with-the-rule (J0) and oblique (JX) components. Preoperative predictors of postoperative refractive astigmatism in the second eye were determined by multivariable regression.

Results: The postoperative refractive astigmatism in the first eye predicted 40% of the variation in the second eye (r²=0.40; P < .001). The multivariable model to predict postoperative with-the-rule astigmatism was

\[ J_{PostopEye2} = (0.376 \times J_{PostopEye1}) + (0.327 \times J_{KeratomEye2}) + (0.097 \times J_{PreopEye2} - 0.099 \]  

\[ (P < .001 \text{ for first 2 terms}; r^2 = 0.56). \]

The multivariable model for oblique astigmatism was

\[ J_{XPostopEye2} = (0.350 \times J_{XKeratomEye2}) + (0.231 \times J_{XKeratomEye1}) + (0.064 \times J_{XPreopEye2} - 0.07 \]  

\[ (P \approx .01 \text{ for first 2 terms}; r^2 = 0.20). \]

Conclusions: Refractive with-the-rule astigmatism observed postoperatively in the first eye is a strong independent predictor of postoperative with-the-rule astigmatism in the second eye. Keratometric oblique astigmatism in the first eye is a weak but statistically significant independent predictor of postoperative oblique astigmatism in the second eye. Both findings are consistent with mirror symmetry of the corneas about the midsagittal plane and may improve the prediction (and hence control) of postoperative astigmatism in the second eye.

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Methods

The study was performed after approval by the institutional review board. Surgical procedures for cataract performed at a Veterans Affairs medical center during a 65-month period from January 1, 2004, to May 31, 2009, were reviewed. Inclusion criteria consisted of bilateral sequential cataract surgery, implantation of a hydrophobic acrylic lens (Acrysof SA60AT lens; Alcon Laboratories, Fort Worth, Texas) in the bag, documentation of keratometry and preoperative refraction for both
eyes, and use of the same biometry method (IOL Master system [version 5; Carl Zeiss Meditec, Inc, Dublin, California] or immersion ultrasonography) in both eyes. Exclusion criteria consisted of ophthalmic surgery before cataract surgery, complications during the surgery preventing placement of an intraocular lens in the capsular bag, postoperative macular edema, and postoperative best-corrected visual acuity of less than 20/60 in either eye.

Before 2007, biometry was performed using a keratometer (Bausch & Lomb, Rochester, New York). Beginning in 2007, new patients underwent measurements performed with the IOL Master system if clarity of the optical media permitted.

All patients underwent phacoemulsification with placement of the acrylic lens in the bag. Multiple residents performed most of the surgical procedures. Selection of a 2.8-mm superior scleral tunnel or a 2.8-mm temporal clear corneal incision was based on the preference of the resident and the supervising attending physician and could differ for first and second eyes. Postoperative refraction was recorded 6 to 8 weeks after the operation.

For clear corneal incisions, a triplanar 2.8-mm self-sealing corneal tunnel was prepared with the keratome centered just off the horizontal meridian (eg, at the 8:30 clock position for a right-handed surgeon and a right eye). Stromal hydration was used at the end of the case.

For scleral tunnel incisions, light wet-field coagulation was applied, and then a straight incision 2.8 mm wide and approximately 0.5 mm deep was made with the crescent blade, approximately 1.0 mm behind the limbus, centered just off the vertical meridian (eg, at the 11:30 clock position for a right-handed surgeon). A triplanar, self-sealing corneoscleral tunnel 2.8 mm wide was prepared and the anterior chamber was entered. A suture was placed in scleral tunnel incisions if the surgeons believed the wound was at risk of leaking postoperatively.

**ASTIGMATISM NOTATION**

All preoperative, postoperative, and expected refractions were converted to the power vector components described by Thibos et al.\(^{19,20}\). In this system, refractions are considered to be the sum of the following 3 components: the spherical equivalent, a Jackson cross cylinder oriented at 180° (J \(_0\)) , and a Jackson cross cylinder oriented at 45° (J \(_{45}\)) . The corneas display mirror symmetry; thus, an axis of 45° in the right eye has the same anatomic orientation with respect to the eyelids and other facial structures as an orientation of 135° in the left eye.\(^{17,21}\) Therefore, oblique astigmatism, J \(_{45}\) , was defined as J \(_{45} = J_{1}\) for the right eye and J \(_{45} = − J_{1}\) for the left eye. In this article, J \(_{0}\) is referred to as quantifying with-the-rule astigmatism (although if J \(_{0}\) is negative, the patient has against-the-rule astigmatism). If the astigmatic portion of a refraction includes a cylinder of power C with axis \(\theta_1\), the cross cylinders are calculated with the following equations\(^{19,20}\):

\[
\begin{align*}
J_0 & = -(C/2)\cos(2\theta_1) \\
J_{45} & = -(C/2)\sin(2\theta_1)
\end{align*}
\]

For instance, if a refraction is +5.00 + 3.00 × 100, then C = 3.00, \(\theta_1 = 100\), \(J_{0} = 1.41\) dipters (D), and \(J_{45} = 0.51\) D.

Once the postoperative spherical equivalent (M), J \(_0\) , and J \(_{45}\) are predicted, they are converted to a refraction in positive cylinder notation (S, +C×B\(^{\circ}\)) using the following equations\(^{19,20}\):

\[
\begin{align*}
C & = 2\sqrt{(J_0^2 + J_{45}^2)} \\
S & = M − C/2, \\
B & = 0.5\tan^{-1}(J_{45}/J_0) + 90°.
\end{align*}
\]

**STATISTICAL EVALUATION**

Predicators of the postoperative astigmatic components (J \(_0\) and J \(_{45}\) ) in the second eye were determined by means of univariate and multivariable linear regression analysis. Independent variables analyzed included age, preoperative refractive and keratometric astigmatism in both eyes, and mean preoperative keratometry readings. Nonsignificant variables were removed by stepwise backward regression analysis. We used commercially available software (Statistica, version 7; StatSoft, Inc, Tulsa, Oklahoma) to generate the regression coefficients (m values), coefficient of determination (r\(^2\) values), and statistical significance (P values). To express the model fit in the familiar unit of diopters, the square root of the mean squared (RMS) error was calculated. The squared error for each patient was

\[
C^2 = 4\left[(J_0\text{Observed}−J_0\text{Expected})^2 + (J_{45}\text{Observed}−J_{45}\text{Expected})^2\right].
\]

The RMS error is appropriate for assessing standard least squares regression, which minimizes the squared error.

Keratometric astigmatism will have a greater effect in the spectacle plane for myopic eyes, and a lesser effect in the spectacle plane for hyperopic eyes.\(^{3,22}\) However, after cataract surgery, patients are close to emmetropia; therefore, keratometric astigmatism is almost unchanged when translated to the spectacle plane for typical data sets.\(^{7}\) A related question is whether astigmatism in the preoperative refraction, which deviates more from emmetropia, can be moved to the corneal plane. The present study addressed this question using standard formulas for vertexing spherocylinders to the corneal plane.\(^{1}\)

For analysis of with-the-rule astigmatism, incision location was coded as 1 for superior, −1 for temporal, or 0 for not applicable. For analysis of oblique astigmatism, the incision location quadrant was estimated on the basis of surgeon handedness (eg, a right-handed surgeon performing a superior scleral tunnel incision on a right eye would be expected to produce an incision centered in the superotemporal quadrant) and was coded as 1 for the superonasal or inferotemporal quadrants, −1 for the superotemporal quadrant, and 0 for not applicable.

**RESULTS**

The second eyes of 160 patients who underwent bilateral sequential phacoemulsification were included in the study. Of these patients, 156 (97.5%) were male, and 40 (25.0%) were black. The mean (SD) age was 71.3 (9.9) years. Manual keratometry was used for both eyes in 102 patients (63.8%), and the IOL Master system was used in both eyes in the remainder. The following linear regression showed that the preoperative refractive cylinder power could be moved to the corneal plane without substantial modification: C (in the corneal plane) =0.001 + 0.981C (in the spectacle plane; r\(^2\)=0.987).

Preoperative and postoperative refraction reflected a small amount of against-the-rule astigmatism on average (J \(_{45}<0\); Table 1). For each measure, there was interpatient variability (SD of J \(_{45}\) 0.40-0.49). There was less oblique astigmatism in the keratometry and refraction, as indicated by the smaller mean and SD values for J \(_{45}\) (Table 1). Most patients (95.0%) had an absolute difference of preoperative keratometric astigmatism magnitude of 1.13 D or less and of mean keratometry of 0.85 D or less.

The univariate predictors of postoperative with-the-rule astigmatism (J \(_{45}\) ) in the second eye included age, preoperative refractive and keratometric astigmatism...
(J0) in both eyes, and postoperative refractive astigmatism (JX) in the first eye (all P < .001; Table 2). The best predictors were the preoperative keratometric astigmatism in the second eye (r² = 0.47) and the postoperative refractive astigmatism in the first eye (r² = 0.40; Table 2 and Figure). The following multivariable model predicted postoperative with-the-rule astigmatism in the second eye:

\[
J_{0, PostopEye2} = (0.376 \times J_{0, PostopEye1}) + (0.327 \times J_{0, KeratomEye2}) + (0.097 \times J_{0, PreopEye2}) - 0.099,
\]

where P < .001 for the first 2 terms, and the model r² = 0.56 (Table 2).

The univariate predictors of postoperative oblique astigmatism (JX) in the second eye included the preoperative keratometric astigmatism (JX0) in both eyes (both P < .001) and the preoperative refractive astigmatism (JX0) in the second eye (P = .007; Table 3). The best predictors were the preoperative keratometric astigmatism in the second eye (r² = 0.16) and in the first eye (r² = 0.07; Table 3). We used the following multivariable model for postoperative oblique astigmatism in the second eye:

\[
J_{X, PostopEye2} = (0.350 \times J_{X, KeratomEye2}) + (0.231 \times J_{X, KeratomEye1}) + (0.064 \times J_{X, PreopEye2}) - 0.07,
\]

where P ≤ .01 for the first 2 terms, and the model r² = 0.20 (Table 3). When analyses were conducted with JX5 instead of JX0, refractive and keratometric J50 values in the first eye were negatively associated with postoperative refractive J50 in the second eye, consistent with mirror symmetry of the corneas.17

The RMS error for keratometry alone was 0.72 D. The RMS error for the multivariable models incorporating contralateral eye information in Table 2 and Table 3 was 0.67 D, a reduction of 6.8%.

**PREDICTIVE VALUE OF INCISION LOCATION**

In all, 106 patients (66.2%) had superior scleral tunnel incisions. Of these, 43 (40.6%) had a suture and 68 (64.2%) had the same approach in the first eye. Of the 54 patients with a clear corneal incision, 29 (53.7%) had the same approach in the first eye. Unsutured incisions were associated with a small amount of flattening in the axis of the incision, although the changes were not statistically significant (P ≥ .08; r² ≈ 0.02; Table 1 and Table 2). Sutured incisions had on average no effect on the corneal curvature and no ability to predict refraction (r² < 0.001), although the standard errors for the regression coefficients were 50% to 75% greater than those for the unsutured incisions. This result was consistent with more variability in the effect of sutured incisions. Multivariable models incorporating incision location confirmed the value of the contralateral eye information. For instance, a conventional model incorporating preoperative keratometry for the second eye and sutured and unsutured incision location had an r² value of 0.47 for prediction of postoperative J50 in the second eye, and only the keratometric term was significant (P < .001). Addition of information from the first eye (postoperative refractive astigmatism [JX0; P < .001] and incision location) to the model improved the r² value to 0.57. For
oblique astigmatism, the corresponding conventional model had an r² value of 0.17, with only the keratometric term significant (P < .001). Addition of keratometry in the first eye (P = .03) and incision location improved the r² value to 0.21. The RMS error of the conventional model was 0.75 D, and the addition of the information from the first eye improved the RMS error to 0.70 D, a reduction of 7.1%.

The right eye was the second eye to have surgery in 39.4% of the cases. Laterality of surgery in the second eye was not predictive of postoperative refractive astigmatism (J₀ₑ₂, P = .83; r² = 0.0003; m = 0.01 D) (Jₓₑ₂, P = .09; r² = 0.02; m = −0.06 D). Among the surgical procedures in the second eye, 64.4% were performed by a right-handed surgeon. Right-handedness was a weak predictor of postoperative refractive astigmatism in univariate analyses (J₀ₑ₂, P = .05; r² = 0.02; b = 0.13 D) (Jₓₑ₂, P = .03; r² = 0.03; b = −0.08 D) but, after controlling for ipsilateral keratometry, this relationship was not significant (P = .17 for J₀ₑ₂; P = .07 for Jₓₑ₂).

**SUBGROUP ANALYSIS**

Similar findings were seen in subgroup analysis. In the 102 patients undergoing manual keratometry for both eyes, the multivariable model to predict postoperative with-the-rule astigmatism in the second eye was $J_{\text{PostopEye2}} = (0.254 \times J_{\text{PostopEye1}}) + (0.367 \times J_{\text{KeratomeEye1}}) + (0.123 \times J_{\text{PostopEye2}}) - 0.126$, where $P < .01$ for the first 2 terms, $P = 0.06$ for the $J_{\text{PreopEye2}}$ term, and the model $r² = 0.55$. For these patients, the multivariable model for postoperative oblique astigmatism in the second eye was $J_{\text{PostopEye2}} = (0.225 \times J_{\text{KeratomeEye2}}) + (0.204 \times J_{\text{PostopEye2}}) + (0.074 \times J_{\text{PreopEye2}}) - 0.05$, where the $P$ values for terms 1 to 3 were .06, .19, and .28, respectively, and the model $r² = 0.08$. Compared with ipsilateral preoperative keratometry alone, with an RMS error of 0.77 D, the multivariable models improved the RMS error to 0.67 D.

This study demonstrated that the postoperative refractive with-the-rule astigmatism in the second eye having cataract surgery is predicted by that in the first eye, independent of preoperative keratometry. Moreover, the preoperative keratometric oblique astigmatism in the first eye independently predicts postoperative refractive oblique astigmatism in the second eye, although this association is weaker. The astigmatic predictions represent incremental improvements over ipsilateral keratometry alone. For instance, the absolute increase in the explained variation in with-the-rule astigmatism was 9% (with the $r²$ value improving from 0.47 to 0.56).

Both findings depend on interocular symmetry, which also underlies other algorithms for using the postoperative refraction in the first eye to improve refractive predictions in the second eye. Although there has been some debate about whether corneal shape and refraction exhibit predominantly direct or mirror symmetry, our results add to the body of literature demonstrating mirror symmetry of the corneas about the midsagittal plane. Indeed, mirror symmetry is expected in bilateral organs and is observed, at least grossly, in other features of eye anatomy, such as extraocular muscles and retinal organization. For the corneas, this symmetry may result from genetic factors or from corresponding symmetry of facial structure or eyelid orientation, extraocular muscle tension, or other developmental factors.

Because 95% of the patients had an interocular difference in keratometry readings of less than 0.85 D mean and less than 1.13 D astigmatism magnitude, the method should not be applied for patients with a greater degree of interocular asymmetry until additional data are available.

The very small impact of incision location on refractive astigmatism may be surprising but is consistent with a previous study by our group. Unsutured incisions typically produce flattening in the axis of the incision, although the effect is less prominent with smaller incisions. In a randomized trial comparing a 3.0-mm unsutured superior scleral tunnel incision vs a 3.0-mm unsutured temporal clear corneal incision in patients with at least 0.5 D of against-the-rule astigmatism, the difference between groups in keratometric against-the-rule astigmatism at 1 month was 0.18 D, but there was no group difference in uncorrected visual acuity. Refractive astigmatism, which was assessed in the present study...
and is most important clinically, may not always match keratometric changes because of an opposing effect of the posterior or peripheral cornea. Small effects might be more difficult to define with statistical certainty when there is inconsistency due to the involvement of multiple resident surgeons. In the present study, the incisions that were sutured owing to concern about postoperative leaking probably might have produced a greater than average degree of flattening if left unsutured. Sutured incisions had a net null effect on astigmatism, although there was variability, because the incision might produce flattening or steepening depending on suture tightness.31,32

The degree of astigmatism induced by the incision will likely assume an even smaller role as practices transition to incisions close to 2 mm.33,34 Ideally, surgeons should estimate the surgically induced astigmatism within their own practice.

If confirmed, the regression equations could be used to predict refraction after cataract surgery in the second eye. The findings may be specific to our particular practice, consisting mostly of male patients and multiple surgeons in a teaching environment. In addition, the findings are based on retrospective calculations. The next step in evaluating the clinical value of this strategy would be a prospective randomized trial of adjusting astigmatism control in the second eye on the basis of refractive results in the first eye vs standard care. The uncorrected near and far visual acuity would be an important end point. In studies of toric intraocular lenses, the benefit might be reduced by the fact that lenses are available in discrete increments. Based on the present study, when astigmatism control is contemplated along with cataract surgery, consideration should be given to delaying surgery in the second eye until an accurate postoperative refraction can be obtained in the first eye. An unexpected refractive astigmatic outcome in the first eye should prompt a close evaluation of possible causes, including the influence of posterior or peripheral corneal curvature, which might also be manifested in the results in the second eye.

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REFERENCES


Table 3. Predictors of Postoperative Refractive Jx in the Second Eye

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<th>Univariate Analysis</th>
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<td></td>
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<td>Intercept</td>
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<td>Sutured incision locationb</td>
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Abbreviations: ellipses, not applicable; Jx, oblique astigmatism; m, linear regression coefficient.
a Multivariable model r2=0.20.
b Coded as 1 for superonasal or inferotemporal, −1 for superotemporal, and 0 for not applicable.