Analysis of aggregate surgically induced refractive change, prediction error, and intraocular astigmatism

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ABSTRACT

Purpose: To demonstrate analytical methods for evaluating the results of keratorefractive surgical procedures and emphasize the importance of intraocular astigmatism.

Setting: University of Texas Medical School, Houston, Texas, USA.

Methods: A standard data set, provided by an editor of this journal, comprising the preoperative and postoperative keratometric and refractive measurements of 100 eyes that had keratorefractive surgery was evaluated by 2 methods, vector and spheroequivalent (SEQ) analysis. The individual and aggregate surgically induced refractive changes (SIRCs) and prediction errors were determined from the refractive and keratometric measurements using both methods and then compared. The refraction vertex distance, keratometric index of refraction, and corneal asphericity were used to make the results calculated from refractive data directly comparable to those derived from keratometric data. Doubled-angle and equivalency plots as well as frequency and cumulative histograms were used to display the data. Standard descriptive statistics were used to determine the mean and standard deviation of the aggregate induced astigmatism after converting the polar values (cylinder and axis) to Cartesian (x and y) values.

Results: The preoperative SEQ refractive errors were undercorrected by at least 0.25 diopter (D) in most cases (78%). Six percent were corrected within ± 0.24 D, and 16% were overcorrected by at least 0.25 D SEQ. The mean SEQ was −6.68 D ± 2.49 (SD) before and −0.61 ± 0.82 D after surgery, reflecting a SIRC SEQ of −6.07 ± 2.40 D. The defocus equivalent (DEQ) was 7.41 ± 2.53 D before and 0.96 ± 0.74 D after surgery; for a nominal 3.0 mm pupil, this corresponded to an estimated improvement in uncorrected visual acuity (UCVA) from worse than 20/200 to better than 20/25, respectively. The predictability of the treatment decreased as the attempted refractive correction increased. The average magnitude of the refractive astigmatism was 1.46 ± 0.61 D before and 0.40 ± 0.38 D after surgery. The centroid of the refractive astigmatism was $+0.96 \times 87.9 \pm 0.85$ D, $\rho = 0.43$ before and $+0.11 \times 83.1 \pm 0.37$, $\rho = 0.49$ after surgery. The decrease in the square root of the centroid standard deviation shape factor ($\rho^{1/2}$) indicated an 8% increase in the amount of oblique astigmatism in the population. The prevalence of preoperative keratometric irregular astigmatism in excess of 0.5 D in this group of patients was 13%. The correlation between keratometric and refractive astigmatism was extremely poor before ($r^2 = 0.26$) and especially after surgery ($r^2 = 0.02$), demonstrating the presence of intraocular astigmatism and the limitations of manual keratometry. The centroid of intraocular astigmatism at the corneal plane was $+0.48 \times 178 \pm 0.49$ D, $\rho = 0.59$, and was compensatory.

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Conclusions: The 2 analytical methods are complimentary and permit thorough and quantitative evaluation of SIRCs and allow valid statistical comparisons within and between data sets. The DEQ allows comparison of refractive and visual results. The decrease in refractive predictability with higher corrections is well demonstrated by the SEQ and doubled-angle plots of the SIRC. Doubled-angle plots were particularly useful in interpreting errors of cylinder treatment amount and errors in alignment. The correlation between refractive and keratometric astigmatism was poor for preoperative, postoperative, and SIRC data, indicating the presence of astigmatic elements beyond the corneal surface (ie, intraocular astigmatism). Sources of error in refractive outcome statistics include the use of multiple lens systems in the phoropter, errors in vertex calculations, difficulty in accurately defining the axis of astigmatism, and failure to consider measurement errors when working with keratometric data. The analysis of this particular data set demonstrates the significant clinical benefits of refractive surgery: an 8-fold increase in UCVA, an 11-fold decrease in SEQ refractive error, as well as a 9-fold and nearly a 2 1/2-fold decrease in the magnitude and distribution of astigmatism, respectively. *J Cataract Refract Surg 2001; 27:61–79 © 2001 ASCRS and ESCRS*

The mathematics for calculating surgically induced refractive change (SIRC) was first described in 1849.[1] One hundred twenty-six years later, Jaffe and Clayman[2] properly applied this method to analyze the relationship between cataract surgical technique and the refractive result in individual patients. Since then, several mathematically incorrect methods have been reported.[3–5]

In 1992, to evaluate evolving corneal surgery techniques, we described a method for calculating the surgically induced spherical and astigmatic change in an individual patient.[6] In 1999, we extended the applicability of this method to include aggregate data.[7] The current literature indicates that significant confusion still surrounds the question of how best to evaluate SIRCs.[8,9] We appreciate the opportunity to demonstrate our methods for the 100-case data set provided by Douglas Koch, MD,[9] one of the journal editors.

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Materials and Methods

Statistical analyses and graph preparation were performed on a personal computer using Microsoft Excel 97 and SPSS SigmaPlot 3.0, respectively.

Data Preparation and Sources of Error

Vertexing spherocylinders to the corneal plane. Refractions are normally performed at the spectacle plane or in the phoropter and not at the corneal plane. Refractive measurements must be vertexed to the corneal plane before they can be compared to those obtained by keratometry or topography. Inaccuracies in the measurement of vertex distances and inappropriate application of the vertex formula are frequent sources of error in planning and reporting the results of refractive surgical procedures.

Refractions performed in the phoropter are at a nominal vertex distance of 13.75 mm when the corneal vertex is located at the large mark on the calibration scale. Within the phoropter, multiple lenses are aligned to produce the combination lens used in refraction. This combination lens has an effective vertex distance that frequently differs from the nominal value indicated on the vertex scale. This difference, along with the difficulty of maintaining precise patient alignment, cause the vertex distances measured with the phoropter to be unreliable, especially at higher refractive powers. A more accurate measurement is obtained by performing the refraction over a soft contact lens with a power

near the spheroequivalent (SEQ) of the refractive error.

For example, the SEQ of a −11.50 +2.00 × 90 refraction at the phoropter with a nominal vertex distance of 13.75 mm is −10.50 diopters (D). When vertexed to the corneal plane, the SEQ is −9.18 D. Overefraction of the same patient performed with a −10.00 D soft contact lens gives −2.00 +2.00 × 90. The final refraction at the corneal plane (vertex = 0 mm) is then −12.00 +2.00 × 90, yielding an SEQ refraction of −11.00 D at the corneal plane. The value with the contact lens is −1.82 D more myopic than with the vertexed phoropter refraction. The contact lens method is always more accurate provided the soft contact lens is labeled properly. The correct vertex distance must be entered into all laser and surgically planning software programs to avoid inducing residual refractive errors.

Since the plus and minus cylinder notation for refraction represents a difference rather than an actual power in either meridian, they must first be converted to the cross-cylinder notation before performing vertex calculations. The spherocylindric refraction in this example is vertexed to the corneal plane as shown below:

Cross cylinder form @ spectacle: −12.00 × 180 and −10.00 × 90

Vertex: 13.75 mm

Vertex formula from spectacle plane (REF_s) to corneal plane (REF_c)[10,11]:

$$REF_c = \frac{1000 * REF_s}{1000 - REF_s * \text{Vertex (mm)}} \quad (1)$$

Substituting the values from the example

$$REF_{C1} = \frac{1000 * (-12.00)}{1000 - (-12.00) * 13.75} = -10.30 \text{ D}$$

$$REF_{C2} = \frac{1000 * (-10.00)}{1000 - (-10.00) * 13.75} = -8.79 \text{ D}$$

Cross cylinder form @ cornea: −10.30 × 180 and −8.79 × 90

Vertex: 0 mm

Plus cylinder form: −10.30 + 1.51 × 90

Minus cylinder form: −8.79 −1.51 × 180

When correctly vertexed, the astigmatism at the corneal plane is −1.51 D, almost one half a diopter less than the value obtained by incorrectly vertexing the cylinder portion of the refraction expressed in minus-cylinder notation (−1.95 D). Vertexing a myopic refraction from the spectacle to the corneal plane will always reduce the magnitude of the astigmatism. For hyperopia, the relationship is just the opposite.

To compare SIRCs calculated from refractive and keratometric data, the refractive data must be vertexed to the corneal plane *before* the SIRC calculation is performed. Performing a vertex calculation on the results of a SIRC calculation gives an incorrect answer.

Special considerations with keratometric data. Keratometric data are already at the corneal plane and do not require vertex adjustment. However, an additional issue arises with respect to the correct method of converting the anterior radius of the cornea to the net corneal refractive power. The formula used to convert radii to power is the simple spherical refracting surface formula (SSRS):

$$K_k = \frac{n_2 - n_1}{r} \quad (2a)$$

The variables n_1 and n_2 are the indices of refraction of the first and second media, respectively, and r is the radius of curvature of the interface. The value for n_1 is 1.000 (index of refraction for air). The standardized keratometric index of refraction (1.3375) was chosen for n_2 many years ago.[12] The origin of this value for n_2 remains obscure, appearing to have been arbitrarily selected in the 19th century so that an anterior radius of corneal curvature of 7.5 mm would yield a power of 45.00 D.[13]

$$K_k = \frac{1.3375 - 1.000}{r_a} = \frac{0.3375}{r_a} \quad (2b)$$

where r_a is the anterior radius of curvature of the cornea (m) and K_k is the standardized keratometric net corneal power (D).

The cornea, like any meniscus lens, has a front surface power, a back surface power, and a net or equivalent power. To compute the surgically induced cornea power change, one must know whether the surgical procedure alters the front surface, back surface, or net cornea power. The front surface power and net power changes are the only clinically relevant considerations, since there are no keratorefractive

procedures that are intended to change only the back surface power.

For procedures such as photorefractive keratectomy (PRK), laser in situ keratomileusis (LASIK), and probably radial keratotomy, the change in dioptric power of the cornea is almost entirely due to front surface power changes in the cornea. To compute front surface power, the change in media for the light rays is from air (n = 1.000) to cornea (n = 1.376), so, as Holladay and Waring[13] and Mandell[14] have recommended, the correct formula for computing the power and any change in power would be

$$K_a = \frac{1.376 - 1.000}{r_a} = \frac{0.376}{r_a} \qquad (2c)$$

where r_a is the anterior radius of curvature of the cornea (m) and K_a is the front surface corneal power (o).

The front surface power of a cornea with an anterior radius of 7.5 mm would be 50.13 D (0.376/0.0075), 5.13 D greater than the standardized keratometric power of 45.00 D (0.3375/0.0075). Front surface powers are 11.14% (0.376/0.3375) larger than keratometric values. When determining the change in the refractive power of the eye for procedures that change only the front surface of the cornea, the change computed from keratometry must be increased by 11.14% to compensate for the difference in the index of refraction.

For analyzing results in which it is believed that both the front and back surfaces have been changed equally, it is appropriate to use the net or equivalent corneal index of refraction. The most common application of this conversion is in intraocular lens (IOL) power calculations. There is still debate among investigators as to the most appropriate value for the net or equivalent index of refraction. Binkhorst[15] and Olson[16] have empirically determined this value to be 4/3 and 1.3315, respectively. For standardization purposes,[13] we have recommended adopting the Binkhorst value, since it is has been the one most frequently used for the past 20 years. The equation to compute net or equivalent corneal power, using indices of refraction for air (n = 1.000) and cornea (n = 4/3), would be

$$K_n = \frac{4/3 - 1.000}{r_a} = \frac{1/3}{r_a} \qquad (2d)$$

where r_a is the anterior radius of curvature of the cornea (m) and K_n is the net corneal power (D).

The net power of a cornea with an anterior radius of 7.5 mm would be 44.44 D (1/3 ÷ 0.0075), 0.56 D less than the standardized keratometric power of 45.00 D. Net or equivalent corneal powers are 98.76% (1/3 ÷ 0.3375) of the standardized keratometric values. When the net or equivalent power of the cornea or changes in the net corneal power are needed, the standardized keratometric values must be reduced to 98.76% of their original values to accurately reflect the net refractive power change in the cornea. For net powers of the cornea used in IOL calculations, a 1.24% overestimate of the corneal power results in a 0.56 D error, which is significant and intolerable for these calculations. However, for calculating changes in corneal power produced by refractive surgical procedures, this 1.24% error is clinically negligible. Nevertheless, when reporting net corneal power changes from standardized keratometry measurement, the values should be reduced by 1.24% to be correct.

Another source of difference between keratometric and refractive measurement arises from the relative flattening of the central cornea by myopic refractive surgery.[17,18] Keratometers and topographers sample the paracentral cornea (nominal diameter of 3.2 mm for a 44.00 D cornea) rather than the surgically flattened optical center and thus tend to overestimate the corneal power after myopic refractive surgery. This study found an additional 10% difference between the actual central power change and the paracentral keratometric and topographic change. The refractive power of the cornea changed by a factor 1.21 times more than the apparent keratometric change when considering the progressive flattening error and the front surface index of refraction error.[17,18]

It is important to note that the value of 1.333 for the net corneal index of refraction may change following refractive surgical procedures that alter epithelial thickness or remove corneal tissue (ie, PRK and LASIK). The refractive indices of the epithelium and stroma are different, and there may be subtle intrastromal differences, eg, between Bowman's layer and the posterior stroma.[19] Procedures that alter epithelial thickness could change the refractive power of the epithelium, and removal of stromal tissue could alter the net refractive index of the stroma. These changes could be important in determining the correct value of net corneal power for IOL calculations, since, as

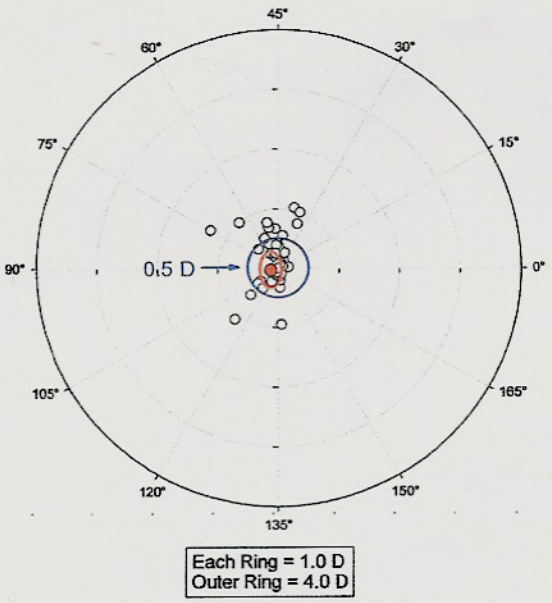

Figure 1. (Holladay) Doubled-angle plot of the non-orthogonal, keratometric irregular astigmatism. The data points represent the difference vector in the original and orthogonalized keratometric astigmatism vector. The centroid is 0.09 D × 57.1 ± 0.23 D, $\rho = 2.86$. The 13 data points outside the 0.50 D radius (blue) would be considered clinically significant irregular keratometric astigmatism of oblique axes.

noted above, a change of only 1% to 2% could produce unacceptably high errors.

Surgically induced refractive change calculations require that the astigmatism is regular, ie, the steepest and flattest meridians must be orthogonal (90 degrees apart). In the data set used here, some cases had non-orthogonal axes. In these cases, the steep axis was maintained and the flat axis was assigned a value 90 degrees away. The vector difference in the original keratometric astigmatism and the orthogonalized values is a measure of the irregular, oblique axes (not oblique axis) astigmatism. These data are shown on the doubled-angle plot in Figure 1. Thirteen eyes had magnitudes greater than the 0.50 D magnitude that is considered clinically significant irregular keratometric astigmatism. All SIRC calculations performed here used the orthogonalized data.

Precision of the magnitude and axis of astigmatism. The question often arises as to what is the angular error in astigmatism that is comparable to a given magnitude error. Intuitively, most clinicians know that the higher the degree of astigmatism, the more accurate the axis of astigmatism must be; eg, a 10 degree error in the axis of

Table 1. Angular error (± degrees) corresponding to a magnitude error (D) at different measurement precisions.

Tolerance (D)	Measured Magnitude (D)						
	0.125	0.250	0.50	1.00	2.00	4.00	8.00
±0.125	30	14	7	4	2	1	0
±0.25	90	30	14	7	4	2	1
±0.50	—	90	30	14	7	4	2
±1.00	—	—	90	30	14	7	4

6.00 D of astigmatism is more significant than a 10 degree error in the axis with 1.00 D of astigmatism. The angular error that is equivalent to a dioptric error for a given astigmatism magnitude is given by the following formula:

$$\theta = \text{ArcSin}\left(0.5 * \frac{t}{M}\right) \qquad (3)$$

where t is the tolerance (precision, eg, ± 0.50 D), M is the magnitude of the astigmatism, and θ is the angular error that is equivalent to the tolerance in diopters. Table 1 tabulates these values, and Figure 2 illustrates their relationship.

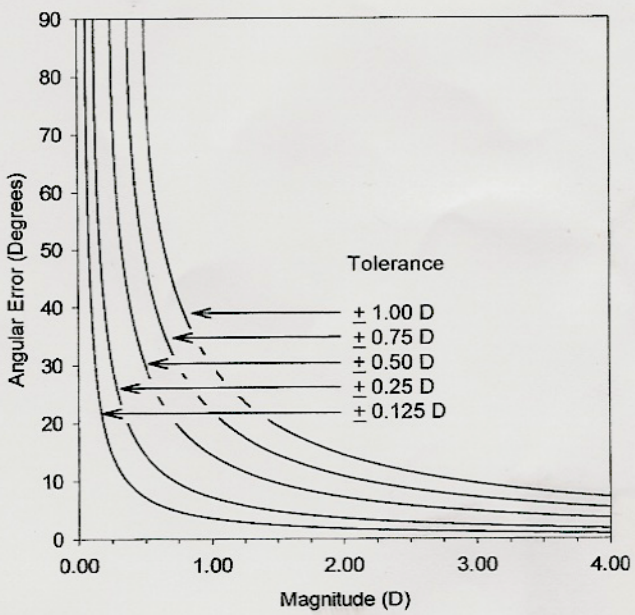

Figure 2. (Holladay) Cartesian plot of the angular error (degrees) that corresponds to a given magnitude error (diopters) at different levels of precision. When the tolerance is equal to the magnitude, the angular error is 30 degrees.