letters

Assessment of Surgically Induced Astigmatism: Toward an International Standard

Central regular corneal astigmatism can be described, in empirical topographical terms, as a dome with an elliptical base. By definition, the elliptical base has a long axis and a short axis at right angles to each other. Astigmatism is commonly described by the difference between the curve of the dome on the long axis and on the short axis and the direction of 1 axis. Surgery for astigmatism alters the dome by changing the elliptical base or alters the dome itself. This is a simple concept, so why is it so difficult to describe the changes in optical astigmatism brought about by surgery?

Some of the difficulty arises from historical ways of describing astigmatism and some from the assumptions of first-order optics. These can be characterized in the following way:

1. The description of astigmatism on the basis of the hemimeridia of the superior cornea; i.e., the 0 to 180 degree description of axis. This assumes that the 2 hemimeridia on each axis are symmetrical, while providing a duplication of descriptive terms for the horizontal meridian.

2. Astigmatism can be legitimately described in refractive, conventional keratometric, and videokeratoscopic terms. Furthermore, some authors describe refractive astigmatism in terms of spectacle correction and others make corrections to the corneal plane.

3. Differing cylinder sign conventions describe the same shape.

4. The derivation of corneal curvature values from keratometry relies on assumptions of paraxial optics that are not applicable in the mid- and far-periphery of the cornea.

5. Since the outcome of astigmatic correction depends on the axis as well as the magnitude of the toric change, and magnitude can be affected by axis variation and vice versa, vector analysis is necessary to examine the changes that take place in the cornea with surgery.

For ease of reporting and comparability of results we should pick, where possible, standard values from the parameters that have alternate descriptions or at least state clearly the conventions being used. For example, to facilitate comparison between refractive and corneal measures of astigmatism, refractive errors should be analyzed at the corneal plane. Imposing standard methods of recording data like this or insisting on 1 cylinder sign convention (another example of entrenched practices) may prove difficult and is, perhaps, less pressing than standardization of methods of data analysis. In response to the standard for assessing and reporting surgically induced astigmatism (SIA) suggested by Naeser,[1] we would like to propose a simpler approach.

There are 2 types of SIA analysis. The first is analysis of the effect on astigmatism of a particular intervention that is not necessarily intended to reduce cylinder power; e.g., the SIA of cataract wound incisions or spherical photorefractive keratectomy (PRK). The second is analysis of SIA by an intervention whose specific intent is to alter (usually reduce) astigmatism in a predictable manner with regard to axis and cylinder power; e.g., toric excimer treatments or arcuate keratotomy. The methods of analysis, as Naeser pointed out, have to be sufficiently robust to allow analysis of individual cases and aggregate data.[1] The important features of the analysis depend on the outcome measure of interest. For instance, if visual outcome alone is of interest, the absolute magnitude of the remaining cylinders is more important than its axis. Simple data on remaining astigmatism or cylinder subtraction analysis may be enough to describe the outcome for that purpose. Alternatively, if the impact of surgery on corneal shape is of interest, vector analysis is required. Additionally, if one has a specific aim for the intervention, measurement of success or failure and analysis of how to improve the outcome require setting a target as described by Alpins.[2]

Analysis of SIA When the Intent Is Not Necessarily to Reduce Cylinder Power

For this form of analysis, 3 things have to be elucidated.

1. The effect on the curvature of the cornea at the axis of the surgery in which the surgery is carried out at a specific axis (e.g., cataract surgery). In the simplest terms, this requires measurements before and after surgery on that axis and simple comparison of magnitude or power. Aggregate data could be analyzed by mean, standard deviation, and comparisons by whatever tests of significance were appropriate. As an alternative to direct measurement, these data could be derived by vector analysis from preoperative and postoperative corneal astigmatism values and the surgical axis. Alpins has described such techniques.[3] Curvature change in the cornea at any meridian can be derived by vector analysis to give the flattening, steepening, and torque (or "axis shift," free of magnitude change) that has taken place.

2. Surgically induced astigmatism in vector terms. Magnitude and direction can be derived by whatever method is thought to be most appropriate.[2,4] This kind of analysis is necessary to examine the change in astigmatism brought about by treatments that affect all axes simultaneously (if not equally) as in "spherical" PRK. Alternatively, comparison of direction with a surgical meridian, e.g., a cataract wound, can be undertaken by assigning a plus or minus sign to the direction of "misalignment" of the SIA with the meridian in which the surgery was performed. Usually, this would involve assigning a plus for SIA placed anticlockwise to the site of surgery and a minus for that placed clockwise. Subtracting the surgical axis from the SIA axis, using the 180 degree axis convention and zero rather than 180 degrees to describe the horizontal meridian, will yield such signs. A measure of the accuracy of alignment would then be the standard deviation of a mean of a number of observations.

3. Simple subtraction of the cylinder powers, using 1 cylinder sign convention, independent of axis, before and after the procedure. Of course, this form of analysis gives us no information on surgical events in the cornea; vector analysis is necessary for that. However, since for higher cylinder powers the effect on the patient's vision is governed more by the power of the astigmatism than the axis, this kind of analysis is important in terms of visual outcome.

These methods could also be used to describe corneal curvature changes induced by disease or injury.

Analysis of SIA in Which the Intent Is to Alter (Usually Reduce) Cylinder Power

The crucial elements in this sort of analysis are setting a target and analyzing how the SIA fits with the targeted induced astigmatism (TIA).[2] This step allows measurement of degrees of success and modification of subsequent surgery to improve results. Without a target, we have no method to assess whether we have achieved the desired result. The standard for reporting proposed by Naeser[1] lacks such a target. Even if the target remaining astigmatism is always zero, the change required in each case to achieve this must be given a numerical value to allow analysis of degrees of overtreatment, undertreatment, or misalignment. For a sample of eyes, the mean SIA, where each eye has different preoperative and postoperative astigmatism, has little meaning. However, the proportion of the astigmatic target achieved (Alpins' correction index [SIA/TIA] or its inverse, the coefficient of adjustment) facilitates modification of subsequent treatments.[2,5]

To accomplish this, obviously SIA and TIA have to be derived, each with direction and magnitude. The question of how well these derived values coincide can then be addressed in individuals and in aggregate data. Alpins suggests a number of indexes of accuracy and outcome based on the SIA, TIA, and torque vectors.[2,3,5–7] Analysis of aggregate direction data, comparing SIA with TIA, using the sign method described above, deriving means and standard deviations, allows us to assess the accuracy of axis placement of treatment, Alpins' "angle of error."[2] Well-placed treatments will have differences between SIA and TIA orientations near zero and small standard deviations of the mean. The minimum data that should be reported to allow most of these analyses are the SIA and TIA vector magnitudes and orientations.

For this kind of surgery, in which residual surgical astigmatism power should approach zero (i.e., where SIA should equal TIA), the axis of remaining astigmatism becomes more important. In fact, it may be desirable, in selected cases, to leave with-the-rule myopic astigmatism for its putative benefits for near visual acuity. In these circumstances, "cylinder subtraction" analysis becomes less meaningful. However, where large cylinder power may remain after surgery (e.g., following refractive surgery for postkeratoplasty astigmatism), it is probably worth reporting remaining astigmatism because of the impact on visual outcome.

We would argue that in using vector analysis, we combine the numerical descriptors of astigmatism (cylinder power and axis) in a unified mathematical expression (a vector with magnitude and direction), allowing us to calculate astigmatic change in terms of power/magnitude and axis/direction, where these 2 values vary in an interdependent way. This allows us to look at each of the 2 values independently. The key to analysis of aggregate data lies then in the comparison of achieved surgical effect to a target since, as Naeser points out,[1] analysis of surgical effect alone is often meaningless.

In summary, the following minimum data should be reported in studies of the changes in astigmatism brought about by surgery.

For analysis of astigmatic change in which the intent is not necessarily to reduce cylinder power:

1. Preoperative refractive or keratometric measurements
2. The surgical axis, where one exists
3. Preoperative corneal curvature on that surgical axis
4. Postoperative corneal curvature on that surgical axis
5. Postoperative refractive or keratometric measurement
6. Surgically induced astigmatism, magnitude, and direction.

For analysis of SIA in which the intent is to alter cylinder power and/or axis:

1. Preoperative refractive or keratometric measurements
2. The surgical axis
3. The target astigmatism to remain after surgery (axis and magnitude)
4. Postoperative refractive or keratometric measurements
5. Surgically induced magnitude and orientation
6. Targeted induced astigmatism magnitude and orientation.

From this data set, various indexes of outcome can be derived. For more comprehensive reporting, Alpins[2,3,5] has described methods of vector analysis appropriate for almost all forms of astigmatic change.

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Format for Reporting Surgically Induced Astigmatism on Aggregate Data

In the March issue, the journal editors suggested a standard format for reporting refractive surgical data.[1] For surgically induced astigmatism (SIA), the editors recommended "vector analysis" or "more advanced astigmatic analysis, as described by Alpins[2] and by Holladay and coauthors."[3] The former of these statements is directly wrong, while the latter can be questioned.

Vector analysis can be performed by a variety of methods,[4,5] which yield identical results. In a previous letter,[6] I demonstrated that vector analysis yields a systematic error when used on aggregate data. Vector analysis, disregarding axis and calculating the change in astigmatic magnitude in any direction, overestimates the true change in astigmatism. Unfortunately, most published studies of SIA have used vector analysis, meaning that the derived conclusions are misleading and dangerous to follow in a clinical context. Vector analysis is obsolete and its widespread use among refractive publications embarrassing; it will not be discussed further. I will use this opportunity for a brief systematic review.

For reporting SIA, expressions of both mean value and spread are necessary. The problem is that astigmatism is traditionally characterized by 2 incompatible variables; namely, magnitude expressed in diopters and direction expressed in degrees. However, any net astigmatism may unequivocally be characterized by 2 polar values.[6,7] Subsequent calculations can only be performed with these polar values, while the final result may be retransformed to a net astigmatism. The problem can be approached in a univariate or a bivariate manner:

Univariate Approach. Analysis of astigmatic direction and magnitude is restricted to preselected and interesting meridians. This produces the polar values of the surgical meridian[8,9] and the oblique meridian[7]; the former expressing the effective flattening of the surgical meridian, the latter the torque or rotation of the cylinder. The flattening of the surgical meridian is actually the goal of astigmatic surgery and accounts for the overwhelming proportion of SIA. Therefore, this magnitude, albeit not quite specific and representing a data reduction,[8] is a valid and simple indicator of the effect of the surgical procedure. The mean, variance, and confidence interval for polar values are calculated in the normal manner.

Bivariate Approach. It is possible to describe astigmatic magnitude and direction simultaneously using classical bivariate statistical methods.[10]

1. Means. The mean of several astigmatisms is simply the combined mean of the 2 polar values. These 2 means may be retransformed to a net astigmatism of specific direction and magnitude. I recently described this method.[6,7] A similar method, in which the variables used are mathematically identical to the polar values at 90 and 135 degrees, was later reported by Holladay and coauthors.[3] The problem of finding the mean of several cylinders, which has caused considerable controversy in ophthalmology, was actually discussed and solved several years ago in journals devoted to optometry and optics.[11–13]

Holladay and coauthors[3] have introduced the doubled-angle plot. This graphical analysis is rather unfortunate, as the objective of transforming net astigmatisms to polar values is to get rid of the incommensurable angles, expressed in degrees. Reintroduction of "doubled-angle" is therefore unnecessary and confusing.

2. Confidence regions. In univariate analysis, the confidence region is an interval. In bivariate analysis, the confidence region is an area delineated by an ellipse, the location and configuration of which is determined by the means and standard deviations for and the correlation coefficient between the 2 polar values. A univariate, statistically significant difference between the means of the polar values will usually indicate a significant difference between 2 surgical techniques. However, in borderline significance this may not hold true, as the bivariate standard deviations are modulated by the correlation coefficient between the 2 polar values. The bivariate comparison of means always produces the correct result. The use of bivariate statistics in assessing SIA has been reported at meetings and discussed in a paper.[14] The theory of bivariate statistical analysis may seem complicated. Fortunately, most major statistical software packages now have facilities for bivariate analysis, allowing for immediate assessment of all aspects of SIA.

As refractive surgeons, we should exhibit not only technical excellency but also sufficient mental dexterity to allow us to assess our craft. Obviously, we should be no less knowledgeable than our colleagues in optometry and optics. The advice on reporting SIA, given by the journal editors, should be revised in accordance with current scientific evidence derived from ophthalmological and basal visual scientific sources.

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Assessment of Surgically Induced Astigmatism: Toward an International Standard II

We would like to make a few comments in response to the recent article by Holladay and coauthors.[1] The authors deal well with the basic difficulties of reporting astigmatic change discussed in our previous letter. The advantages of expressing astigmatism in the cross-cylinder format and using doubled angles are well demonstrated. However, there are several unsubstantiated assertions and an important omission.

Holladay and coauthors "introduce" a form of measuring outcome against a target and limit this to an attempted complete correction of astigmatism. First, not all treatments have to aim at zero astigmatism and second, Alpins has extensively described the use of a targeted induced astigmatism (not always zero) in at least 3 publications.[3–5] The earlier 2 were published in time for inclusion by Holladay and coauthors, yet none were cited. It is notable that the Alpins technique has much wider application (nonzero targets, deliberate alteration of axis, etc.).

The authors describe a method of analysis of aggregate data on astigmatism using the *x* and *y* coordinates of doubled-angle plots as the basic data for deriving means and standard deviations. Presumably, this is to avoid separating the direction and magnitude data. However, the reason given is that for descriptive statistics the components of astigmatism must be orthogonal, an assertion that requires further explanation. They go on to explain this statement by saying that the principle is similar to the preferred use of LogMAR data for statistical analysis of acuity data. This is not the case. The use of LogMAR notation is to render acuity data in a linear instead of a geometric scale and allow simple statistical manipulation. The problem here is quite different. We would assert, furthermore, that in vector analysis, handling magnitude and orientation data separately is legitimate as long as the techniques of vector analysis are properly applied. This is one of the major purposes of vector analysis. Holladay and coauthors give no more substantial reason for their technique.

If one concedes that angle plots are a useful graphical method of displaying aggregate data on remaining astigmatism, there is no clear advantage of doubled-angle plots for this purpose, and analysis by other means need not lead to erroneous results, despite their unsubstantiated assertions to the contrary. The tendency for horizontal flattening is as well demonstrated in Figure 5B (single angle) as in 5A (doubled angle).

Finally, in their abstract, the authors mention that their method is the "best." This would suggest that they applied some form of standard comparison of their method with others. Other good methods have already been described,[2–4] yet no such comparison is presented. While we support their efforts to establish a standard of recording and analysis, we would disagree that their method is the "best."

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Reply: We appreciate the comments by Drs. Goggin and Pesudovs and appreciate the opportunity to reply.

First, we are well aware of Alpins' work and contributions. We respectfully disagree with some of the assertions about discrepancies between refractive astigmatism, topographic astigmatism, and surgically induced astigmatism (SIA) made by Alpins and others. Because of this disagreement with his methodology, we made no comments or conclusions that used information from his articles and therefore made no reference to them in our article.

The basis of our disagreement involves the difference between astigmatism measured by refraction and that found by corneal topography or keratometry. We believe there are only 2 ways this can occur: (1) when lenticular astigmatism is present or (2) when irregular corneal or lenticular astigmatism is present, which causes the conversion to regular astigmatism to be ambiguous, resulting in disparities.

In either case, we believe the prescription measured by refraction to be the appropriate value to "add" to the cornea (e.g., program into the laser) to achieve emmetropia. If the target is not zero, e.g., if it is −0.50 diopter (D), the appropriate treatment is still calculated using the well-established cross-cylinder solution first described by Stokes[1] and more recently by us.[2] We have never required the target to be zero; we simply require the prediction error to be the difference between the desired postoperative refraction and the actual postoperative refraction.[3] This is not new, since we and many others have been using this methodology for over 20 years for intraocular lens power calculations and determination of prediction error.[4,5]

Second, our comment that descriptive statistics cannot be applied to polar coordinates is true because the 2 parameters are not independent (orthogonal in statistical space). The simple example of computing the average of +1.00 × 179 and +1.00 × 001 vividly illustrates this point. In polar coordinates, the average of the magnitude is +1.00 [(1.00+1.00)/2)], and the average of the axes is 90 degrees [(179+001)/2)], yielding a result of +1.00 × 90. Clearly, this is close to the correct magnitude, but the axis is completely wrong—it is 90 degrees off. This incorrect answer is produced because the magnitude and axis are not independent (orthogonal) parameters and therefore cannot be treated independently. Converting to the doubled-angle Cartesian coordinates (*x*, *y*), +1.00 × 179 becomes (+0.9998, −0.0012) and +1.00 × 001 becomes (+0.9998, +0.0012). The average of *x* is +0.9998, and the average of *y* is 0.0000. Converting back to polar coordinates, we have +0.9998 × 0, which is the correct answer.

Our analogy with visual acuity and LogMAR values was simply to illustrate the principle of converting from one notation system (decimal) to another (LogMAR) before statistics can be applied.[6] Our point is that statistical analysis cannot be directly performed on decimal visual acuities, just as it cannot be directly performed on astigmatism in polar coordinates.

We would like to use this opportunity to make a distinction between the values for mean astigmatic change in a population versus the average magnitude of the surgically induced change. The former value is calculated as noted above, whereas the latter is the mean of the individual absolute values for surgically induced change. To use another example, we calculate these values for 2 eyes with SIA of +1.00 × 90 and +1.00 × 180, respectively. Using the method described in our article, the doubled-angle Cartesian coordinates become (−1.0000, 0.0000) and (+1.0000, 0.0000), respectively. The average of these is (0.0, 0.0), which converts to polar coordinates of 0 D of mean induced astigmatism. This represents the trend of the population as a whole and is the centroid of the data points. The mean of the value for the magnitude of SIA, however, is (1 D + 1 D)/2, or 1 D. This is the mean value for magnitude of the SIA, and it is equally important (with standard deviations and ranges) for describing the SIA. This value statistically is often referred to as the "mean deviation."

We still believe the doubled-angle plots and Cartesian coordinate system provides the best method for analyzing and displaying data because of mathematical and statistical validity and graphical clarity. Indeed, this type of format is becoming the required standard for astigmatic data reporting for the *Journal of Cataract & Refractive Surgery*[7] and the *Journal of Refractive Surgery* (George Waring III, MD, personal communication). Finally, we believe there is more to be done in this area and look forward to further advances in techniques of statistical analysis and graphical depiction of astigmatic change.—*Jack T. Holladay, MD, MSEE, Douglas D. Koch, MD*

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Note: See editorial on page 1545.

FROM THE EDITOR

Reporting astigmatism data

Does it seem easier to correct astigmatism than to analyze astigmatism data? This is certainly a conclusion that one could reach after reading this month's letters to the editor and reviewing recent literature on this topic.

We are grateful to Drs. Goggin and Pesudovs and Dr. Naeser for the thoughtful comments in their letters (pages 1548 to 1553). It is essential that refractive surgical articles use standardized, meaningful, and understandable criteria for reporting astigmatic results.[1] Although it appears that we are approaching this goal, their letters and the response of Holladay and Koch highlight the controversies that still exist. I would like to try to reframe the discussion.

To understand the astigmatic outcome of a procedure, we need 2 basic types of information: (1) the outcome from the patient's perspective and (2) the change produced by the procedure. The former describes the end result, whereas the latter indicates how that result was achieved.

To understand the results from the patient's perspective, the following elements are essential:

- Uncorrected visual acuity
- Mean, standard deviation, and range of actual postoperative astigmatism (refractive or corneal)
- Arithmetic change in astigmatism (refractive or corneal)
- Some measure(s) of surgically induced irregular astigmatism, including change in best spectacle-corrected visual acuity or contrast sensitivity. (Analysis of irregular astigmatism is another critical area in need of much further work.)

Obviously, 2 of these parameters contain no astigmatic data per se; rather, they reflect in part the effect of astigmatism on the patient's vision.

To understand how a procedure alters astigmatism, the analysis is more complex, and here the major differences in opinions arise. As a bare minimum, I suggest that the following are required:

- Vector analysis of the magnitude (in diopters) of surgically induced change (mean, standard deviation, and range).[2] Naeser dismisses this as "obsolete," but it is a crucial reporting element. Vector analysis indicates the magnitude of surgically induced change, which we must know if we are to understand the effect of the procedure. Certainly, vector analysis should not be the sole means of reporting astigmatic results.
- Analysis of aggregate data.[3,4] This polar coordinate value represents the trend for the population as a whole and indicates the mean magnitude and angular direction of the surgically induced change. Typically, in calculating this value for a series of patients, vectors in different directions partially cancel out one another; hence, the magnitude of this value is usually much smaller than the mean magnitude of the individual vectors for surgically induced change.

What else should be considered? Naeser recommends bivariate analysis with confidence intervals. As Goggin and Pesudovs state, additional parameters may be required if the surgical goal is to reduce pre-existing astigmatism; options include polar values[5] and the parameters described by Alpins.[6-8] Another crucial area is topographic analysis of astigmatic change, which, like the analysis of irregular astigmatism, requires much additional work.

Where do we go from here? In a future issue, we would like to facilitate a broader discussion of various analytical approaches. We will supply a refractive surgical data set to several experts and ask them to analyze the astigmatic results and explain their rationale. Their responses will be published, permitting us to compare methods, solicit input from our readers, and work toward a consensus. Ultimately, our goal is to identify methodology--and available software--that permits all of us to analyze our astigmatic data simply, uniformly, and meaningfully.

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