GUEST EDITORIAL

Pursuing perfection in intraocular lens calculations

IV. Rethinking astigmatism analysis for intraocular lens-based surgery: Suggested terminology, analysis, and standards for outcome reports

We saved our perhaps most controversial topic for this fourth editorial: analyzing astigmatic change following IOL-based surgery, that is, cataract surgery and refractive lens exchange. This topic is challenging for three major reasons:

1. **Range of analytical approaches.** In the January 2001 issue of JCRS, several authors described their methods for analyzing change in corneal astigmatism following laser in situ keratomileusis surgery. Several of these methods are commonly and effectively used in peer-reviewed scientific studies to characterize astigmatic changes.
2. **Analyzing astigmatic change in intraocular lens (IOL)-based surgery is more complex than in corneal refractive surgery.** One issue is simply the transition of terminology and standards for reporting outcomes from corneal laser refractive surgery to toric-IOL-based surgery, which was recently addressed by a joint editorial in the *Journal of Cataract & Refractive Surgery* and the *Journal of Refractive Surgery*.[1] A larger problem is complexity of measurement and analysis. With corneal refractive surgery, we evaluate changes in two measurable entities: refraction and anterior corneal curvature. With IOL-based surgery, however, parameters required to analyze astigmatic change after cataract surgery include: (a) refraction; (b) anterior corneal astigmatism; (c) posterior corneal astigmatism,[2,3] which still eludes consistently accurate measurement; (d) IOL alignment, which must be rigorously measured; (e) effective IOL toricity at corneal plane, which can be calculated but not directly measured; and (f) IOL tilt,[4,5] which induces astigmatism with nontoric and toric IOLs.
3. **There are four clinical scenarios in which cataract surgery alters ocular astigmatism.** They are: (a) nontoric IOL without corneal relaxing incisions, (b) nontoric IOL with corneal relaxing incisions, (c) toric IOL without corneal relaxing incisions, and (d) toric IOL with corneal relaxing incisions. Since both the cornea and IOL have an astigmatic component (tilt in the case of a spherical IOL), for each of these scenarios we are interested in the corneal, IOL-induced, and total ocular astigmatism (which is typically characterized by the manifest refractive astigmatism, but objective measures of ocular astigmatism can also be used).

In this editorial, we propose (1) simplified terminology that can be used for both IOL and corneal-based refractive surgery and (2) a hybrid approach to astigmatism analysis that we feel is clear, comprehensive, and valuable to clinicians and researchers alike while recognizing the merits of other approaches.

SUGGESTED TERMINOLOGY

Traditionally, terminology for data analysis in IOL-based surgery includes terms such as predicted (or attempted/targeted) versus actual (or achieved) refraction. The difference between the actual and the predicted refraction is defined as the prediction error.

We think that the terms "predicted," "actual," and "prediction error" are inherently clear and lend themselves to use in all types of refractive and cataract surgery. With that in mind, we propose the following terminology:

- **Predicted SIA (surgically-induced astigmatism)**: the astigmatic change that the surgery was designed to produce.
- **Actual SIA:** the astigmatic change that the surgery produced.
- **SIA prediction error:** the vector difference between the above 2 terms: (actual SIA) − (predicted SIA).

As was mentioned above and discussed elsewhere,[1,6] in toric-IOL-based surgery, the term *SIA* should be further refined to clarify the source of the induced change in astigmatism. Hence, we would like to suggest the following refined terminology:

- **SIA_{Cornea}:** the change in total corneal astigmatism. This change can be induced either by the cataract incisions alone or by additional corneal incisions, such as limbal relaxing incisions and astigmatic keratotomy.

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- **SIA_{IOL}:** the astigmatic change induced by a toric IOL, due to its toricity, and by either a toric or nontoric IOL, due to tilt and/or decentration.
- **SIA_{Total}:** the total astigmatic change induced by the surgery.

We further suggest the use of the phrase "postoperative refractive astigmatism" for analysis of routine IOL surgery with the following terminology:

- **Predicted postoperative refractive astigmatism:** the predicted postoperative refractive astigmatism at the corneal plane.
- **Actual postoperative refractive astigmatism:** the postoperative manifest refractive astigmatism at the corneal plane.
- **Postoperative refractive astigmatism prediction error:** the vector difference between the actual and the predicted postoperative refractive astigmatism.

Change in Corneal Astigmatism

The SIA_{Cornea} is the change in corneal astigmatism induced by the cataract surgical incisions and by any relaxing incisions that are also performed.[1] Estimation of SIA_{Cornea} is essential in surgical planning, whereas postoperative measurement of corneal astigmatism should be used to analyze outcomes of toric IOL surgery.

The predicted SIA_{Cornea} is a vector. Traditionally, SIA for a defined cataract incision is calculated as the mean vector magnitude for the case series, independent of vector angle. However, the meridional direction of these vectors can be highly variable. For example, if SIA_{Cornea} for one eye is 0.4 diopter (D) @ 180 and for another is 0.4 D @ 90, the mean magnitude is 0.4 D, but the mean vector is zero. The mean vector, or *centroid*, accurately incorporates both magnitude and meridian and is the proper value to use. This can be calculated using online tools.[A]

However, there are complexities even for this ostensibly simple calculation:

1. **Case-to-case variability.** Depends on incision features (location, architecture including width and length, stretching) and inherent corneal biomechanical features (corneal radius, thickness, rigidity).
2. **Accuracy of the corneal astigmatism measurements.** As mentioned above, currently there is no accurate method to measure the total corneal astigmatism. Hence, there is no accurate method to measure the actual SIA_{Cornea}.
3. **Relatively low repeatability of the corneal astigmatism measurements by standard measuring devices.** Figure 1 shows double-angle plots of the differences in corneal astigmatism measurements (same eyes), in healthy volunteers 5 to 10 days apart, using several measuring devices.[B] In theory, the differences between each pair of astigmatism measurements should be near zero; however, the relatively large 95% confidence ellipses reflect the limitation in assessing the actual SIA_{Cornea} for an individual case.
4. **Stability of the actual SIA_{Cornea} over time.** Postoperative corneal measurements are typically performed 3 to 4 weeks postoperatively, although corneal stability conceivably may not occur until 3 or 4 months postoperatively.
5. **Recent studies** suggest that the magnitude of the SIA_{Cornea} may vary depending on preoperative astigmatism magnitude and the incision location relative to the corneal steep meridian.

An obvious way to mitigate the variability introduced by SIA_{Cornea} is to measure corneal curvature postoperatively. We believe that this is valuable for studies that evaluate toric IOL outcomes.

This analysis is almost always based solely on measured changes in anterior corneal astigmatism, when in fact we want to know changes in total corneal astigmatism. Until we have validated methods for measuring posterior and hence total corneal astigmatism, changes in total corneal astigmatism will most often be considered equivalent to anterior corneal changes.

Change in Astigmatism Induced by the Toric Intraocular Lens

The SIA_{IOL} refers to the change in astigmatism that is induced by the toric IOL at the corneal plane. The SIA_{IOL} prediction errors are caused by some combination of incorrect estimation of the effective cylinder power of the toric IOL at the corneal plane, toric IOL misalignment, difference in actual versus labeled IOL spherical and toric power, and IOL tilt or decentration.

Toric IOL calculation formulas provide a value for the estimated refractive astigmatism after inserting and precisely aligning a given toric IOL. Until recently, most commercially available toric calculators used a fixed ratio of a given IOL's toricity to refractive astigmatism to calculate the astigmatic effect of a toric IOL at the spectacle plane (fixed ratio toric calculator). For example, if the manufacturer's stated value for IOL toricity is 2.00 D, this value is translated to the spectacle plane. However, a more accurate way is to modify the effective toricity based on the spherical power of the IOL and the predicted effective lens position (ELP)[7] (vergence toric calculator). Table 1 gives examples of the impact of ELP and IOL power on effective IOL toricity.[C] Software that provides this calculation includes the Holladay IOL Consultant,[D] the Barrett toric calculator,[E] and many of the new updated online commercial toric calculators.

To predict the IOL toricity at the corneal plane, a conversion from the spectacle plane to corneal plane is required. To do this, one should first convert the predicted postoperative refraction at spectacle plane to a cross-cylinder format and then vertex each of the two values using this formula: $Power_{Corneal\ Plane} = (Power_{Spectacle\ Plane}) / (1 - [Power_{Spectacle\ Plane}] \times [\text{vertex distance in m}])$. Then, the difference between these two is the correct value for effective toricity at the corneal plane: $SIA_{IOL\ Corneal\ Plane}$.