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**Assessment of surgically induced astigmatism: toward an international standard**

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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 one 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 brought about by surgery in terms of optical astigmatism? Some of the difficulties arise due to historical ways of describing astigmatism and others from the assumptions of first order optics. These difficulties can be characterised in the following way:

1. The description of astigmatism on the basis of the hemimeridia of the superior cornea, i.e. the  $0^{\circ}$  to  $180^{\circ}$  description of axis. This assumes that the two 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 effected 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 those parameters that have alternate descriptors 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 analysed at the corneal plane. However, imposing standard methods of recording data like this, or insisting on one cylinder sign convention (another example where practices are entrenched) may prove difficult and is, perhaps, less pressing than standardisation of methods of analysis of data. So, in response to the standard for assessment and reporting of data on surgically induced astigmatism (SIA) suggested by Naeser,<sup>(1)</sup> we would like to propose a simpler approach.

It would appear that there are two types of analysis of SIA. Firstly, analysis of a particular intervention with regard to its effect on astigmatism, but where the intervention is not necessarily intended to reduce cylinder power. Examples of this would be the SIA of cataract wound incisions or spherical PRK. The second is analysis of SIA where the specific intent of the surgery 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, need to be sufficiently robust to allow for analysis of individual cases and aggregate data.<sup>(1)</sup> The important features of the analysis depend on the outcome measure of interest. For instance, if visual outcome, alone, is of interest, then the absolute magnitude of the remaining cylinder 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 then vector analysis is required. Additionally, if one has a specific aim for the intervention, then measurement of success or failure and analysis of how to improve outcome require the setting of a target as described by Alpins.<sup>(2)</sup>

### **Analysis of SIA where the intent is not necessarily to reduce cylinder power.**

For this form of analysis, three things need to be elucidated.

1. *The effect on the curvature of the cornea at the axis of the surgery where 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 analysed by mean, standard deviation and comparisons made by whatever tests of significance were appropriate. As an alternative to direct measurement, these data can be derived by vector analysis from pre- and post-operative corneal astigmatism values, and the surgical axis. Alpins has described such techniques.<sup>(3)</sup> Curvature change at any meridian in the cornea 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. *SIA in vector terms.* Magnitude and direction can be derived by whatever method is felt most appropriate.<sup>(2,4)</sup> This kind of analysis is necessary to examine the change in astigmatism brought about by treatments that effect all axes simultaneously (if not equally), like “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 where the surgery was performed. Usually, this would involve assigning a plus for SIA placed anti-clockwise to the site of surgery and a minus for that placed clockwise. Subtracting the

surgical axis from the SIA axis, using the  $180^0$  axis convention and zero rather than  $180^0$  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 one 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 where the intent is to alter (usually reduce) cylinder power.**

The crucial elements in this sort of analysis are the setting of a target and analysis of how the SIA fits with the targeted induced astigmatism (TIA).<sup>(2)</sup> This step allows measurement of degrees of success and modification of subsequent surgery to improve results. Without a target we have no method of assessing whether we have achieved the desired result. The standard for reporting proposed by Naeser lacks such a target.<sup>(1)</sup> 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 over-treatment, under-treatment or misalignment. For a sample of eyes, the mean SIA, where each eye has a different pre-operative and post-operative

astigmatism, has little meaning. However, the proportion of the astigmatic target achieved (Alpins' Correction Index (SIA/TIA) or its inverse, the Co-efficient of Adjustment) facilitates modification of subsequent treatments. <sup>(2,5)</sup>

To accomplish this, obviously a SIA and a TIA need to be derived, each with direction and magnitude. The question as to how well these derived values coincide can then be addressed in individuals and in aggregate data. Alpins suggests a number of indices of accuracy and outcome based on the SIA, TIA and torque vectors. <sup>(2,3,5,6,7)</sup>

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". <sup>(2)</sup> Well placed treatments will have differences between SIA orientation and TIA orientation near zero and small standard deviations on 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, where 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 to leave, in selected cases, 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 (for example, following refractive surgery for post-keratoplasty 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 two values vary in an inter-dependent way. This then allows us to look at each of the two 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, <sup>(1)</sup> analysis of surgical effect alone is often meaningless.

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

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

1. Pre-operative refractive or keratometric measurements.
2. The surgical axis, where one exists.
3. Pre-operative corneal curvature on that surgical axis.
4. Post-operative corneal curvature on that surgical axis.
5. Post-operative refractive or keratometric measurements.
6. SIA, magnitude and direction.

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

1. Pre-operative refractive or keratometric measurements.
2. The surgical axis.
3. The target astigmatism to remain after surgery (axis and magnitude).

4. Post-operative refractive or keratometric measurements.

5. SIA magnitude and orientation.

6. TIA magnitude and orientation.

From this data set, various indices of outcome can be derived. For more comprehensive reporting, Alpins has described methods for vector analysis appropriate for almost all forms of astigmatic change. <sup>(2,3,5)</sup>

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