19 Astigmatism Surprise After Refractive Surgery

Noel Alpins and George Stamatelatos

Core Messages

- Misalignment of the surgical treatment is the major source of refractive surprise in relation to astigmatism.
- Sources of misalignment include cyclotorsion from the seated to supine position, a physical turning of the patients head or intentionally placing a cataract incision on a meridian other than the steepest corneal meridian due to ergonomic factors or to more accurately neutralise the corneal astigmatism using a toric IOL.
- Corneal incisions, no matter how small, should be analysed vectorially to determine what effect, if any, they have had on the preoperative corneal astigmatism.
- Refractive cataract surgeons employing a technique to correct astigmatism at the time of surgery (toric IOLs, LRIs, etc.) need to consider the effect of the phaco incision on the remaining astigmatism; otherwise, the IOL or LRI will be misaligned and/or undercorrected.
- The forces acting to change the corneal structure in a misaligned treatment are flattening (or steepening) and torque. These result in a reduction (or increase) of astigmatism at the intended meridian and also a change (rotation) in the meridian of the astigmatism. (Furthermore, placing the toric IOL at an axis that is not the steepest corneal meridian or the toric IOL rotating over time.)
- Vector analysis is a useful tool to calculate the effects of a misaligned treatment on the remaining astigmatism.

The ultimate goal of modern refractive surgery is to meet, or even exceed, the expectations of the patient. In regard to the spherical component of the correction, this involves obtaining the intended target, which is not necessarily emmetropia. However, concerning the astigmatic component, the universal primary goal is to achieve the maximum reduction of astigmatism. The secondary goal is to ensure any remaining cylinder, unable to be eliminated from the optical system due to corneo-refractive differences, is optimised towards a more favourable with-the-rule orientation.

Addressing the correction of astigmatism is crucial for the refractive surgeon as a large majority of patients have significant preoperative cylinder. Ninety percent of the population has detectable astigmatism, with 25% having more than 1.0D [1]. An uncorrected astigmatic error of 1.0D will, on average, decrease visual acuity to the level of 20/30 or 20/40 depending on its orientation [2]. Aside from blurring of vision, uncorrected astigmatism can also cause distortion, glare, asthenopia, headaches and monocular diplopia.

Surgical treatments that incorporate astigmatic correction include excimer laser surgery such as photoastigmatic refractive keratectomy (PARK), laser in situ keratomileusis (LASIK) and laser-assisted subepithelial keratomileusis (LASEK) including epi-LASEK. These procedures have been shown to be effective at correcting low to moderate levels of astigmatism [1, 3, 4]. However, 15–20% of cataract patients also have >1.5D of astigmatism [5], and with advances in technology, the modern cataract surgeon must also consider the treatment of astigmatism as part of the surgical goal. This is particularly true as refractive clear lens exchange surgery is widely becoming more popular, and these patients tend to be young and demanding of excellent visual results. Options for correcting astigmatism at the time of cataract surgery include placing the phaco incision along the steepest corneal meridian [6–8], paired opposite clear corneal incisions along the steepest meridian [9], phakic [10] and pseudophakic [11, 12] toric IOLs, limbal relaxing incisions (LRIs) [13], peripheral corneal relaxing incisions (PCRIs) [5], and astigmatic keratotomy (AK) [14].

N. Alpins, AM., FRAZCO., FRC.Ophth, FACS. (✉)
NewVision Clinics, 7 Chesterville Road,
Cheltenham, VIC 3192, Australia
e-mail: alpins@newvisionclincis.com.au

G. Stamatelatos, B.Sc. Optom.
NewVision Clinics, Melbourne, Australia

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19.1 Misaligned Treatments

In many cases an astigmatic postoperative surprise is due to the treatment being misaligned with the steepest corneal meridian, otherwise known as 'off-axis'. An unplanned misaligned treatment not only changes the magnitude of the astigmatism in a manner different than intended but will also impact on the orientation of the astigmatism. A wavefront-guided laser surgery designed to correct higher-order aberrations may in fact induce significant aberrations if misaligned, even if the astigmatic component is minimal. This is noticeable for treatments misaligned by only 2 degrees [15], and the room for error is tightened even further in patients with large pupils of 7 mm or more [16]. With such tight criteria, it is important to understand the causes of misalignment, the forces that act to change the cornea in a misaligned treatment and how to analyse outcomes of misaligned treatments to improve future results.

19.2 Sources of Misalignment

The underlying cause for off-axis treatments may be something as simple as a slight misalignment of the patient's head. There are, however, other factors that need to be considered.

19.2.1 Cyclotorsion

As the position of the eye changes, it undergoes natural rotational movements around the central axes known as cyclotorsion. The amount of cyclotorsion depends on the individual and the fixation stimulus but is usually within 15° of the resting position [15]. In relation to refractive surgery, it is the amount of torsion when the patient moves from the seated position to supine that is important, which is typically between 2° and 7° [15]. Therefore, the meridian of the astigmatism measured by the keratometer or topographer where the patient is seated upright may significantly change as the patient lies down for surgery, resulting in a treatment that may be misaligned by up to 7°. This is well outside the recommended 2° limit for a wavefront-guided ablation.

With such a high level of precision required, many laser machines now incorporate tracking systems to account for cyclotorsion by identifying iris landmarks and rotating the treatment accordingly from the wavefront machine to the laser machine. While off-axis effects are a little more forgiving in cataract surgery, alignment errors can be minimised by marking the corneal meridian for toric IOLs or LRIs with the patient seated in an upright position or using computer-assisted guiding systems such as the Alcon Verion™ and Zeiss Callisto eye®.

19.2.2 The Elusive 'Astigmatically Neutral' Incision

The size of the clear corneal incision used to access the anterior chamber for cataract surgery has reduced in recent times. The routine 3 mm incision has moved to sub-2 mm with the gaining popularity of microincisional cataract surgery (MICS), whether bimanual or coaxial. Many surgeons would claim the incision to be 'astigmatically neutral' and therefore do not include it in their surgical calculations. However, while the astigmatism induced by the surgery is certainly reduced with smaller incisions, an astigmatic analysis of the surgically induced astigmatism vector (SIA) to quantify the amount is still required. Any incision, no matter how small, may still have an impact on the corneal structure and will alter the astigmatic magnitude and/or direction.

Therefore, a toric IOL or LRI may be placed exactly where the surgeon intended, yet if the effects of the incision (change in magnitude and orientation) are not taken into account, the results will still be compromised. The final visual outcome may still be acceptable to the patient depending on how much alignment error occurs [17]. However, if there is a thorough understanding of the forces at play during surgery, a merely acceptable outcome can be optimised to an even better one.

19.3 Understanding and Analysing Misaligned Treatments

19.3.1 Forces that Act to Change the Cornea

There are several forces that act to influence the cornea throughout the course of incisional and ablative surgery. *Flattening* and *steepening* of the cornea are the forces most commonly considered as these are the basic underlying principles of refractive surgery. In a perfect surgery, the cornea is flattened at the steepest meridian (or steepened at the flattest meridian or a combination of both) to reduce the magnitude of the astigmatism. However, if the treatment is not perfectly aligned and applied off-axis, another component becomes evident. This component is known as *torque*, which has two effects on the remaining astigmatism: it acts to increase the magnitude and also to rotate the meridian in a clockwise or counterclockwise direction [18]. It is the torque component that is commonly disregarded, yet this is the major source of postoperative surprises in relation to astigmatism. In order for any refractive surgeon (excimer laser or IOL) to achieve maximum results, a thorough understanding of these forces is required.

19.3.2 Vector Analysis of Outcomes

As astigmatism has both magnitude and direction, it may be represented by vectors, and therefore vector analysis is a simple and effective tool for analysing the astigmatic outcomes from surgery [2, 18–20]. The *target induced astigmatism vector (TIA)* is the astigmatic change the surgery was intended to induce, and the *surgically induced astigmatism vector (SIA)* is the astigmatic change actually induced by the surgery. The various relationships between the SIA and TIA can determine whether too much or too little treatment was applied and whether the treatment was aligned effectively or not.

The amount of misalignment is the *angle of error* (AE) and is described by the angle subtended between the SIA and TIA. The AE is positive if the SIA lies in a counterclockwise (CCW) direction to the axis of the TIA, and similarly the AE is negative if the SIA lies in a clockwise (CW) direction relative to the TIA. In a misaligned treatment, the SIA acts to change the cornea in two ways: a proportion of the induced change will act to rotate the astigmatic meridian (through the effect of torque) and the remaining proportion will act to flatten the cornea at the intended meridian. This latter change is known as the *flattening effect* (FE) measured in dioptres and is dependent on the AE:

FE = SIA cosine 2AE.

It can be seen from the above formula that the FE is equal to the SIA when the AE is zero and the treatment is perfectly aligned. The effective proportion of flattening achieved is the *flattening index* (FI) and is equal to the FE divided by the TIA. The relationship between the amount of misalignment and the amount of flattening is seen in Fig. 19.1. This model assumes a full correction of astigmatism is achieved (i.e. the SIA = TIA). It is seen that the FI is reduced as the AE increases. When the treatment is misaligned by 30°, the effective proportion of flattening at the intended axis is reduced by half, with the other half being the torque effect. When the misalignment is 45°, there is no flattening effect at all, and the only force acting to change the cornea is torque. If the misalignment is greater than 45°, there is a negative flattening effect (i.e. the cornea is steepened).

It is a common misconception to regard a misaligned treatment as causing an undercorrection in the magnitude of the astigmatism. However, this is not strictly correct. An over- or undercorrection is determined by the *correction index* (CI), which is the ratio of SIA to TIA. The CI is equal to 1.0 if a full correction of astigmatism occurs. If the CI is greater than 1.0, an overcorrection has occurred, and similarly a CI of less than 1.0 indicates an undercorrection. In a misaligned treatment, the magnitude of the SIA is in fact unaffected as it is independent from the AE, and therefore the CI is also unaffected. Instead a misaligned treatment results in a shift of the orientation of the existing astigmatism (through the effect of torque). The effect of the misaligned treatment on the remaining astigmatism magnitude and axis can be seen in Figs. 19.2 and 19.3.

19.3.3 Example

Let us look at an example to demonstrate. This form of analysis applies for both laser and incisional surgery, so we use a general example that can be used for all refractive surgery. A patient scheduled for refractive surgery has 2.0D corneal astigmatism at a 25° meridian. The surgeon performs uncomplicated surgery

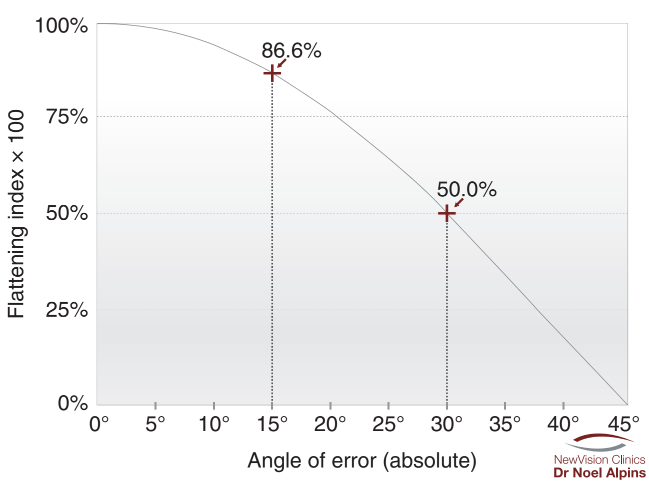

Fig. 19.1 (Alpins) Effect of misaligned astigmatism treatment on flattening index when SIA = TIA

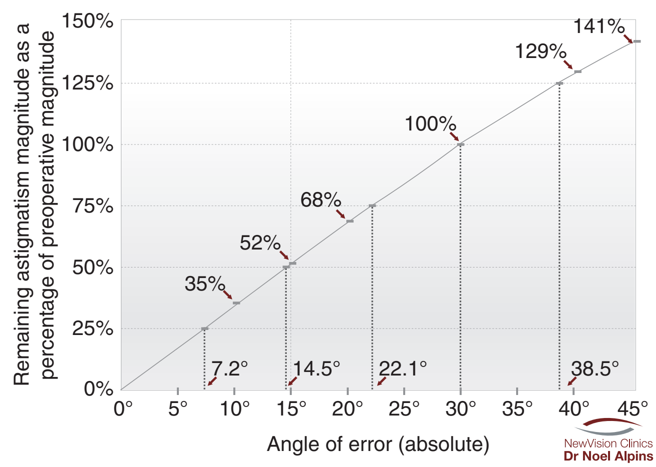

Fig. 19.2 (Alpins) Effect of misaligned astigmatism treatment on remaining astigmatism magnitude

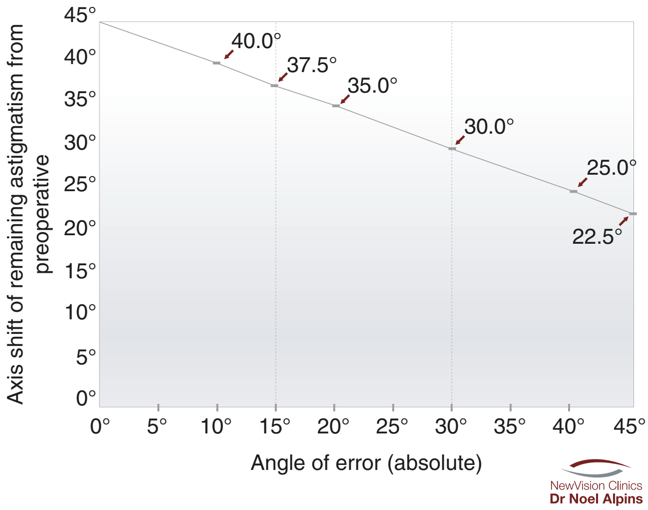

Fig. 19.3 (Alpins) Effect of misaligned astigmatism treatment on remaining astigmatism axis

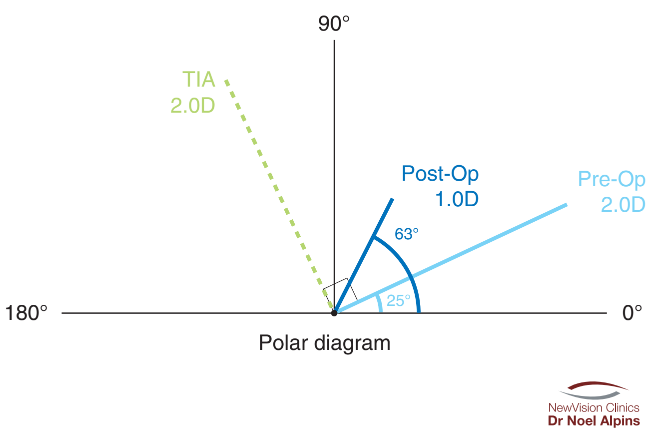

Fig. 19.4 Polar diagram displaying the pre- and postoperative status as it appears on the eye. The TIA is the intended astigmatic treatment and is perpendicular to the preoperative value

that was thought to be aligned correctly, but postoperatively the corneal astigmatism is measured again and found to be 1.0D at 63°. Why did this happen?

A polar diagram is a simple way to represent astigmatism as it appears on the eye. This is seen in Fig. 19.4, where the preoperative value of 2.0D at 25° is represented by the light blue line, and similarly the dark blue line represents the postoperative value of 1.0D at 63°. The TIA represents the amount of astigmatic change the surgeon wants to induce. A reduction of astigmatism may be achieved either by flattening the cornea at 25° or by steepening the cornea at the perpendicular meridian of 115°. However, as the TIA always represents a steepening force, it is displayed on the polar diagram at the perpendicular meridian of 115° as seen in Fig. 19.4. In this example the magnitude of the TIA is equal to that of the preoperative value as the surgery was intended to achieve a full correction of astigmatism.

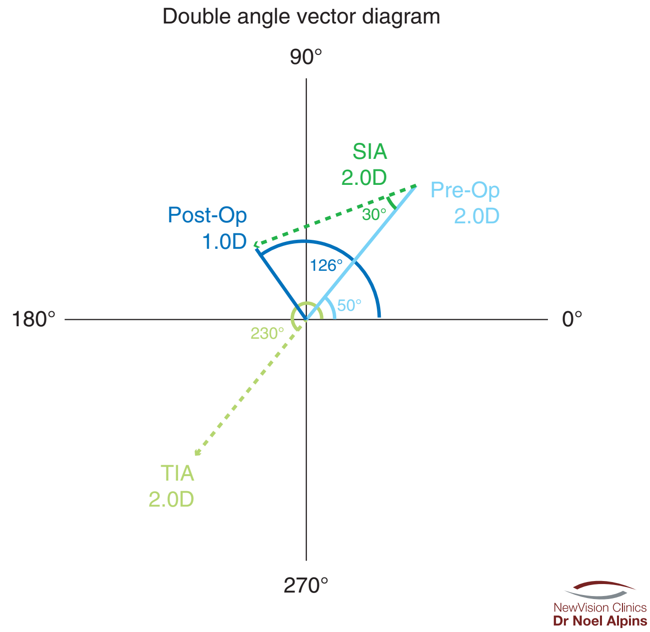

Fig. 19.5 Double-angle vector diagram to allow analysis of the outcome. All the angles have been doubled without altering the magnitudes. This allows calculation of the SIA vector

To allow analysis of the results, the polar diagram (which represents the situation as it appears on the eye) must be converted to a mathematical construct. This is easily done by doubling all the angles to create a double-angle vector diagram (DAVD) as seen in Fig. 19.5. The magnitudes remain unchanged, and the angles are simply doubled.

The SIA is the vector joining from the pre- to the postoperative values. This vector may be moved to the origin without changing the magnitude or the angle as seen in Fig. 19.6. The SIA and TIA in this example are equal in length, indicating a full correction of astigmatism and a correction index of 1.0. Therefore, even though the amount of flattening and thus the reduction in astigmatism magnitude at the intended meridian were less than expected, there has not been an undercorrection of astigmatism magnitude. The angle between the SIA and TIA may then be easily measured at 30°. A line is drawn perpendicularly between these two vectors to give the FE, which in this case is 86.6% the length of the TIA. This represents almost a 15% loss of flattening effect at the intended meridian.

In order to represent this in ‘real’ terms on the eye, the DAVD is converted back to a polar diagram by simply halving the angles, again leaving the magnitudes unchanged, as shown in Fig. 19.7. The angle between the SIA and TIA (i.e. the AE) is now 15°. It is therefore easily seen that the treatment was actually applied 15° off-axis in a CW direction.

Therefore by vector analysis, the loss of flattening effect at the intended placement of the astigmatism treatment (whether incision or ablation) is around 15% when the treatment is 15° ‘off-axis’ from the intended meridian. This relationship

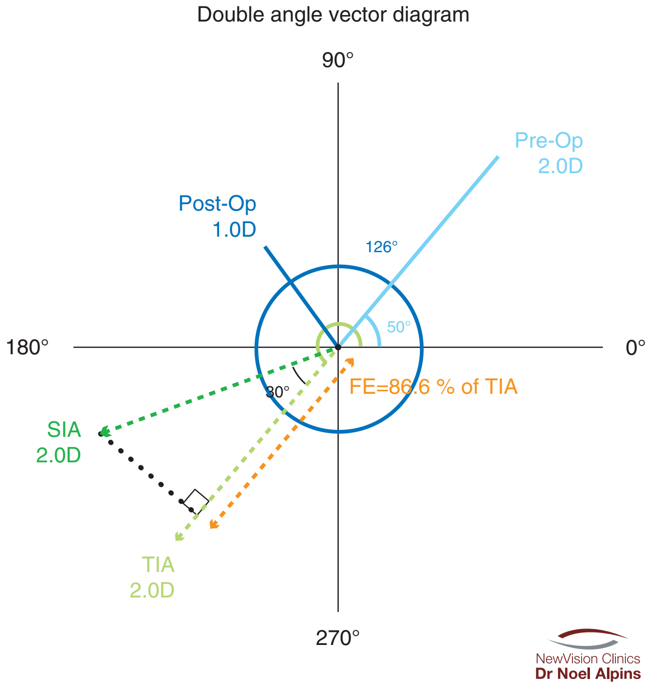

Fig. 19.6 Double-angle vector diagram where the SIA has been moved to the origin without altering the angle subtended or the magnitude. This allows calculation of the flattening effect

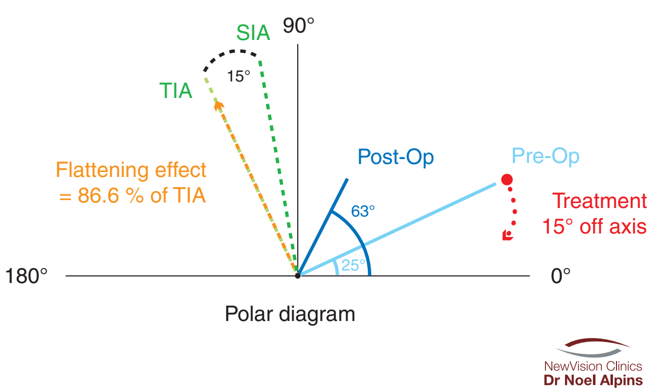

Fig. 19.7 Polar diagram representing the analysis as it would appear on the eye. The angles have been halved without altering the magnitudes. The AE subtended by the SIA and TIA is 15°, so it is easy to see the treatment was misaligned by this amount

between the AE and FI correlates with Fig. 19.1. The remaining 13.4% of the SIA acted as torque to rotate the remaining astigmatism. Figures 19.2 and 19.3 display the effect of misalignment on the remaining astigmatism magnitude and axis. It can be seen from these graphs that a misalignment of 15° in this example reduces the magnitude of the astigmatism by approximately 50% and shifts the meridian by 37.5°. This correlates with our example where the astigmatism was reduced by half and rotated from 25° to 63°. It is important to note in this example that this reduction is just a scalar comparison of pre- and postoperative astigmatism magnitudes.

19.3.4 Practical Use in the Clinical Setting

Imagine the surgery in the above example was cataract surgery and the surgeon was to perform LRIs at the time of cataract surgery to correct the astigmatism. If the incision wasn't taken into account, the LRI would be centred around 25°, based on the assumption that the preoperative value of 2.0D at 25° hadn't changed. In fact, the effect of the cataract incision has changed the astigmatism to 1.0D at 63°. The LRI would therefore have been misaligned by almost 40°. Similarly if a toric IOL was implanted at the preoperative meridian of 25° to correct 2.0D of cylinder, a postoperative surprise would have occurred as the real astigmatism correction should have been 1.0D at 63°.

Therefore, if a surgeon assumes the incision is neutral and does not place the incision along the corneal meridian, the misalignment will change both the meridian and magnitude of the astigmatism that are being treated. The amount of change will obviously depend on the amount of misalignment but also on the amount of induced flattening by the incision. Each surgeon will achieve a certain average value of corneal flattening depending on the incision size used and the orientation of the incision at the limbal meridian. Due to the ovoid shape of the cornea, incisions placed vertically have a greater flattening effect than those placed temporally as they are slightly closer to the centre of the cornea. Each surgeon ideally should track the data from previous cases to calculate their own average amount of flattening for each site of placement which can then be used when planning future cases.

The ASSORT® toric IOL calculator (freely available at www.assort.com) allows the surgeon to calculate the effect of the incision on the preoperative corneal astigmatism and incorporate this into the surgical plan, using simple vector analysis.

19.3.5 Calculating the Effect of the Incision

A patient scheduled for right eye cataract surgery has 2.0D astigmatism at 30° measured by keratometry. The surgeon intends to use a temporal (180°) clear corneal incision for cataract extraction and then use LRIs to correct the remaining astigmatism. Thus, the incision will be deliberately off-axis by 30°, so what will this do to the remaining astigmatism? From analysing their previous data, the surgeon knows the average flattening induced by their temporal incisions is approximately 0.5D. Therefore, they would expect the TIA vector (which is always perpendicular to the incision as it represents a steepening force) to be 0.5D at 90°. This is represented on the polar diagram in Fig. 19.8.

Again, we need to convert this to a mathematical construct (Cartesian co-ordinates), so we double all angles

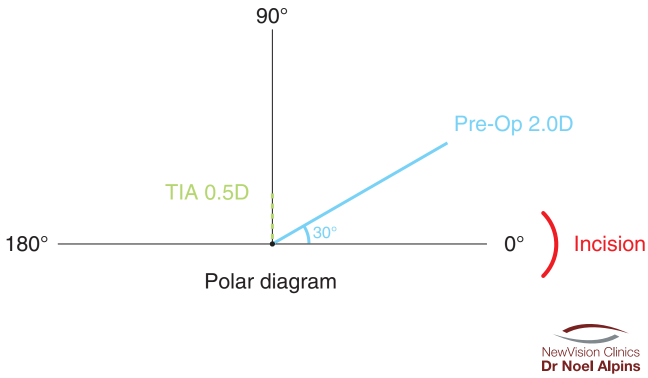

Fig. 19.8 Polar diagram representing the preoperative situation as it appears on the eye. The incision is at 180° and is expected to induce approximately 0.5D flattening. Therefore the expected TIA is perpendicular to this (as the TIA represents a steepening force)

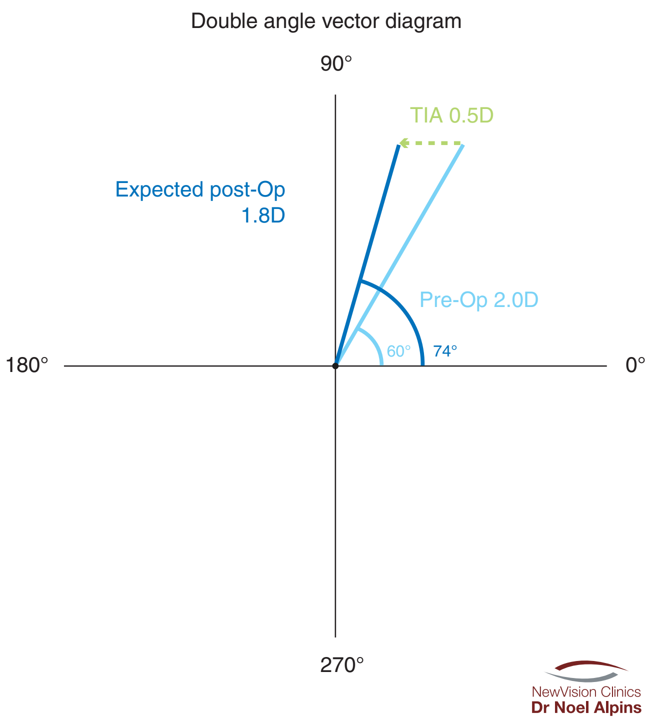

Fig. 19.9 Double-angle vector diagram to allow analysis of the expected outcome. The angles have been doubled without altering the magnitudes, and the TIA vector has been moved to the tip of the preoperative value. This allows calculation of the expected postoperative value

without altering the magnitudes to create a double-angle vector diagram in Fig. 19.9. The preoperative angle of 30° now becomes 60°, and similarly the TIA vector has doubled from 90° to 180°. This TIA vector may be moved to the end of the preoperative value without altering either the 180° angle or the magnitude as displayed in Fig. 19.9.

The expected postoperative value may now be estimated simply by drawing a line from the head of the TIA to the origin. Measuring the length and angle subtended by this line gives a value of 1.80D at 74°. To determine how

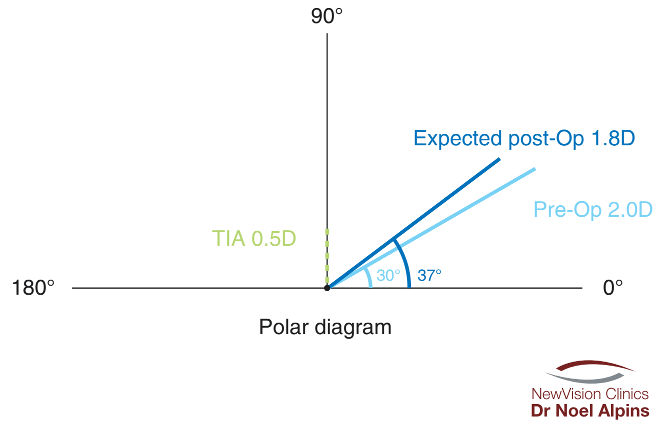

Fig. 19.10 Polar diagram representing the expected outcome as it would appear on the eye. All angles have been halved without altering the magnitudes. By simple measurement, the predicted postoperative astigmatism following the temporal cataract incision is 1.80D at 37°

this will appear on the eye, we revert back to a polar diagram by halving all angles. This is seen in Fig. 19.10, where the expected postoperative value is 1.80D at 37°. Therefore, following a temporal incision, this surgeon should centre the LRI around 37° instead of the preoperative value of 30° (free LRI calculator available at www.assort.com).

19.3.6 Refractive Surprises After Toric IOL Surgery

If there is a refractive surprise post toric IOL surgery as indicated by a significant amount of cylinder remaining in the subjective refraction postoperatively, a toric astigmatic analysis must be performed comparing the postoperative refractive cylinder (corneal plane) to the preoperative corneal astigmatism adjusted for any effect of the phaco incision. The treatment in these cases is the IOL toricity at the corneal plane allowing for the effective lens position and the spherical component of the IOL [21].

Should rotation of the IOL show significant reduction in the refractive cylinder to an acceptable level, then early intervention and rotation of the implants are advised—ideally approximately 4–6 weeks postoperatively.

There are then basically three options available to the surgeon:

1. **Rotate the existing toric IOL to reduce the refractive cylinder to a minimum**.
   Consider rotating the toric IOL when the AE is greater than 10° and the preoperative ORA is less than 0.75D (Fig. 19.11).
2. **Exchange the toric IOL as the toricity selected is too strong or too weak**.

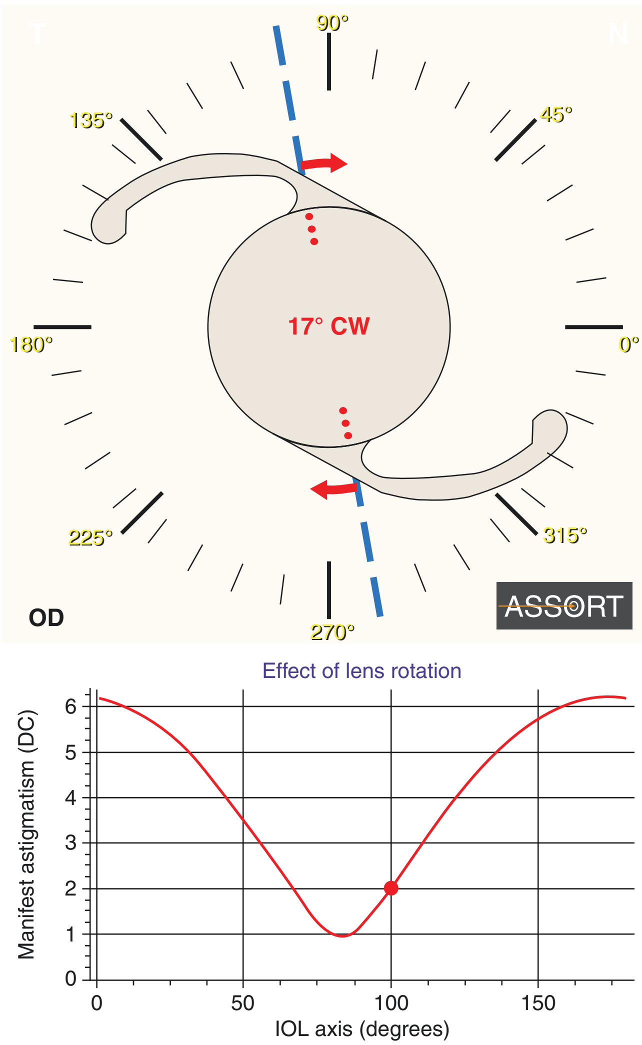

Fig. 19.11 The ASSORT® toric IOL software calculates the rotation of the implanted IOL to improve the postoperative refractive cylinder

In cases where the ME is greater than 1.00D, consider changing the toric IOL to a more suitable cylinder selection OR correcting the refractive cylinder post toric IOL implantation with an additional sulcus toric lens (Fig. 19.12).

3. **Perform excimer laser surgery to correct for any spherical and/or astigmatic error in the subjective refraction.** In cases where the preoperative ORA was greater than 1.25D and the AE and ME are not significant, then excimer laser surgery to correct postoperative refractive cylinder would be an option.
   The significance of postoperative corneal and/or refractive astigmatism can be determined by the steps that the toric IOL of your choice is available in – that is, if the toric IOL comes in 0.75 steps of cylinder and the postoperative corneal astigmatism has changed less than this, or the ME is less than this, changing the toric IOL may not be required.

Alpins method

SIA	2.64	Ax	50
TIA	2.69	Ax	30
Difference vector	1.83	Ax	176
Correction index	0.98		
Index of success	0.68		
Magnitude of error	–0.05		
Angle of error	20 (CCW)		

Fig. 19.12 The Alpins Method can be used to determine if the implanted toricity of the IOL is overcorrecting or undercorrecting the corneal astigmatism. Calculation of the magnitude of error (ME) should ideally be zero: greater than ±0.75D means that an exchange of the toric IOL for a more accurate toric power should be considered

Take-Home Pearls

- When marking the limbus, do so prior to surgery with the patient in the seated position before they lie down. This way it will match the preoperative keratometry or topography meridian where the patient is also seated. This meridian may actually change by 2–7° as the patient lies down due to cyclotorsion of the eyes.
- If a treatment is applied exactly at the steepest corneal meridian, the magnitude of the astigmatism is reduced, and the meridian of any remaining astigmatism remains unchanged.
- If a treatment is applied at a meridian other than the steepest corneal meridian (i.e. a misaligned 'off-axis' treatment), the magnitude of the astigmatism is either reduced or increased, and the meridian of the remaining astigmatism is changed in the opposite direction of the misaligned incision due to the force of torque.
- Many cataract surgeons place all incisions temporally or superiorly regardless of the location of the steepest meridian but then orientate the toric IOL or LRI with the preoperative corneal meridian without accounting for any change in magnitude or direction from the incision. This results in a compromised result with incomplete astigmatism reduction.
- Use vector analysis (www.assort.com) to calculate the effect of the incision on the remaining astigmatism magnitude and meridian prior to performing surgery to optimise results from toric IOLs or LRIs.
- Use vector analysis to calculate the effect of rotating the implanted toric IOL in reducing the manifest refractive cylinder. The Alpins Method of vector analysis can be used to determine if the toric power of the IOL is accurate.

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