Chapter 24

The Cornea - Part X

Treatment and Analysis of Astigmatism During the Laser Era

By

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A fascinating question that can never be asked scientifically without a certain committed effort to comprehend is what is the relationship between golf and better eye sight? Most would certainly reply in a puzzled manner. However, I would reply it started with a want for better astigmatic analysis and ended with a set of principles which would provide the tools required to enable improved analysis of refractive surgery.

When I first began ophthalmology I was motivated by the thought of providing people with better eye sight. This is an enthusiasm that has only increased over time and consequently led me to develop the novel approach to astigmatism analysis which will be explained in this chapter.

In the early 1990s, when I first began to examine astigmatism analysis and treatment to encompass laser modalities, it soon became apparent that there existed a lot of confusion about the best way to analyse and treat 'the unique refractive error' of astigmatism.[1] To begin with, many had simply compared pre and postoperative astigmatism magnitude values alone and completely ignored any change in the astigmatic axis. Inevitably, this rendered all imperfect treatments to be "undercorrections". [2] Others, meanwhile, calculated a mean of the axes.[3, 4] Nevertheless, none of these methods assessed the success of the results nor indicated the extent to which the surgical goals were achieved.

The calculation for surgically induced astigmatism vector (SIA) was initially described by **Stokes** [5] and confirmed for cylindrical lenses by **Gartner** [6] and **Naylor**. [7] However, it wasn't until the work of **Jaffe** and **Clayman** [8] that vector analysis was used to calculate the SIA based on corneal incisions at the 90-degree and 180-degree meridia. Further, it was **Naeser's** [9] technique which calculated polar values of astigmatism which were also outside the 90 and 180-degree meridia, and crucial in interpreting results of surgery that induced polar changes, such as cataract and intraocular lens implantation surgery.

Then came excimer laser technology which introduced the conundrum between incisional and ablation techniques. The planning of the laser treatment posed a significant dilemma. The pertinent question being, should the treatment be planned according to refractive cylinder values as recently introduced with laser refractive surgery, or corneal astigmatism parameters as had been customary with incisional surgery? The inherent concern being thus; why should there be two differing surgery paradigms to obtain essentially the same goal of reducing astigmatism to eliminate the need for spectacle correction?

Over the two prior decades, a multitude of approaches to analysis and treatment prevailed,[10-17] which were often contradictory to each other without any overall consistent set of guiding principles and terminology. A better way to collect and analyse data and perform refractive procedures begged discovering. It was clear to me that refractive, cataract and corneal surgeons required a systematic approach to treatment and analysis of astigmatism that addressed the needs of all these refractive disciplines.

What resulted from many years of research, deliberate and systematic scientific study is a method which assists in the planning and evaluation of corneal refractive surgery of astigmatism for both incisional and ablative laser surgery.[18, 19] Known as **"The Alpins Method"**,[20-29] it determines a treatment path and a defined astigmatic target that in many instances was not zero, even though this has to date been the unanimous preference.

My goal was to move the scientific process forward in a way which would improve patient outcomes and provide surgeons and clinicians with a comprehensive set of principles to rationally analyse astigmatism. I realised that I needed to simplify and standardise this new set of principles and, as a result, I developed an analogy to explain the fundamental concepts of my method with more clarity.

The control and correction of astigmatism to this day has been of great concern to the refractive, cataract and corneal surgeon. The surgeon must not only address and quantify the astigmatism that is to be treated, but calculate targets to quantify errors and adjustments to enable further improvements in visual outcomes and patient satisfaction.

The consensus has been to achieve a zero target and to analyse astigmatism outcomes based on such a zero target. However, in many cases, a non-zero goal is in fact what is being unavoidably targeted due to optical imperfections of the eye and the differing means by which it is being measured. Therefore, a simple analysis is not sufficient and it becomes increasingly clear that a greater understanding of patient results is crucial to further improve astigmatic outcomes.

What ensues is a detailed explanation of the evolution of **The Alpins Method** along with the useful and straightforward golf analogy that facilitate a better understanding of the principles presented.

My entrance into the refractive surgery arena and the need to control astigmatism was initiated by the introduction to intraocular implants into the posterior chamber, along with planned extracapsular surgery in the early 1980's. Emetropia was now the spherical goal. But any astigmatism which was usually suture induced with the large incisions of the time prevented, in many cases, the patient gaining spectacle free vision. With a busy cataract practice, almost a whole morning every week was devoted to selective suture division. Nevertheless, the amount of time required stimulated an early entry into small incision surgery in 1987. My first introduction into the world of dynamic vector analysis was most likely the astigmatic change effect of the selective releasing a tight suture of an extracapsular incision, and which suture of many to divide next.

I traveled to my first AIOIS (American Intraocular Implant Society) meeting in 1984, (now ASCRS) held at the Century Plaza Hotel in Los Angeles to learn more about modern cataract surgery and its refractive refinements. It was a surprise to find the hot topic discussed amongst attendees was the 'new' Radial Keratotomy procedure, introduced into the USA by **Leo Bores** in 1979 from techniques developed by **Svyatoslav Fyodorov** of the USSR. I returned later in the year to attend one of Leo's Radial Keratotomy (RK) courses in Scottsdale, Arizona. One of the highlights of the course, in addition to the surgical treatment of myopia, was the incisional approach to reducing corneal astigmatism. This became part of evolving my armamentarium. I introduced this technique into my surgical practice at that time, and continue to use it to this very day to surgically correct astigmatism.

The patterns for the initial incisional techniques were many and varied and were in most cases attempting to reduce a particular range of corneal astigmatism. They were placed on both sides of the cornea according to the principles espoused by **Richard Troutman**, [12] and were symmetrically centered on the steepest corneal meridian.

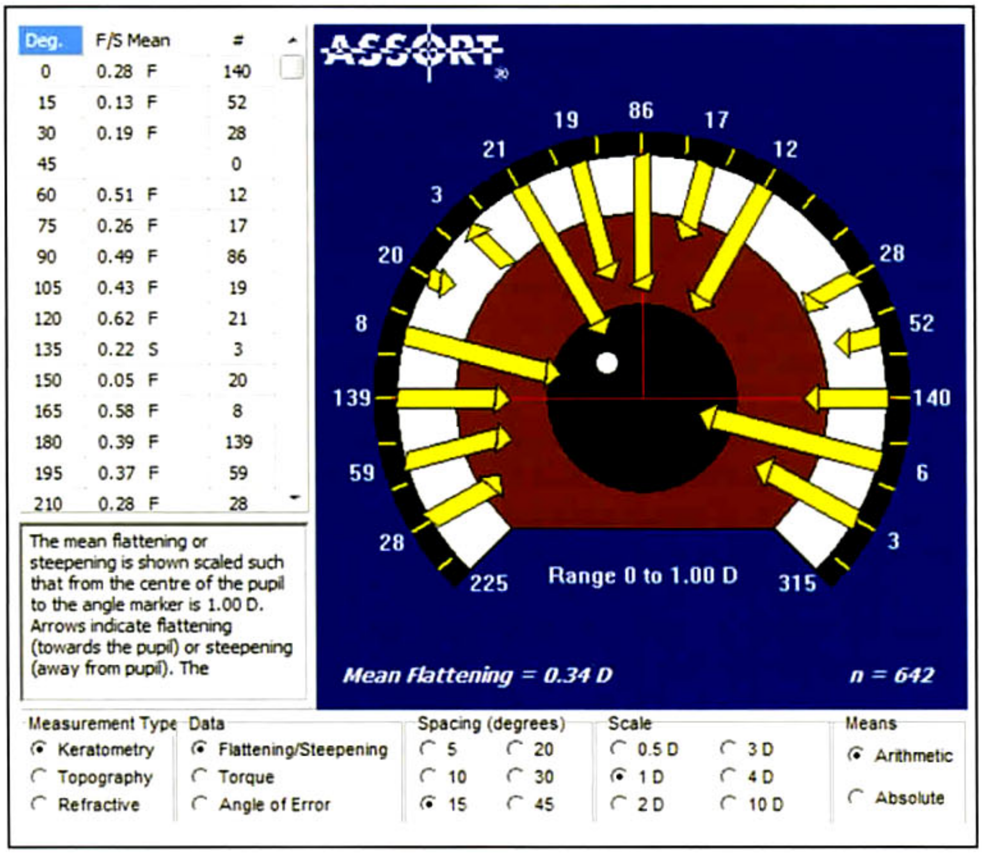
The 'RL' procedure adapted with 5 parallel radial incisions on either side of the visual axis centered on the steep meridian was the earliest attempt at adaptation of the Radial Keratotomy (RK) procedure. However, this soon progressed to one or two of tangential incisions termed Astigmatic Keratotomy (AK) on each side at the 7mm optical zone and 5mm for larger corrections, set with a constant (usually 90%) depth and variable number of incisions to correct up to 2D of astigmatism, along with the IT incision (Interrupted T) introduced by **Robert Hoffman** to gain extra length and effect to straddle either side of a radial incision. For larger amounts of corneal astigmatism, the Ruiz procedure, consisting of four step-ladder incisions surrounded by 2 semi radial incisions to reduce coupling, presented a powerful procedure for up to 6 diopters of astigmatism correction. All these patterns could be performed in conjunction with radial incisions, but avoiding any intersection which could result in wound gape, corneal instability and irregularity. At that time in the 1980's, photokeratoscopes with manual keratometers were the guiding diagnostic devices to quantify parameters and exclude irregularity and keratoconus.

There were a multitude of nomograms available to assist in guiding and refinement of one's own personal nomograms. The concept was to choose one and settle with its dictum for incisions and pattern and subsequently refine it according to ones own results. Those available at that time included **Thornton (Spencer), Lindstrom (Richard), Buzard (Kurt), and Nordan (Lee)**. It soon became evident that tangential incisions were not exclusively acting on the astigmatism, as some net hyperopic shift was occurring, principally as a result of the part radial component of a tangential incision. This stimulated the introduction of the ARC-T incision that followed the circular arc of an optical zone, thus avoiding any part radial myopic-correcting component at all.

With the introduction of phacoemulsification and smaller incisions (5-6mm), with rigid PMMA implants and the development of smaller and foldable implants (3mm and less), cataract surgery became a refractive procedure with astigmatism control becoming a major focus. Most extracapsular surgery was being performed at the superior limbus and may have remained there with the advent of smaller limbal incisions. However, clear corneal incisions stimulated the move to temporal placement and its ergonomic and optical benefits of with-the-rule flattening effect. With the evolution of individual surgeon's changes to their own personal technique, this trend took some time to develop. The introduction of self-sealing incisions by various techniques, including three phase incisions, hinged incisions and wound insufflations, enabled the elimination of sutures and their astigmatic generation effects, providing even earlier visual rehabilitation.

Incisional Keratotomy became part of the surgical technique for reducing corneal astigmatism. It was performed at the time of the cataract surgery and usually immediately prior to surgery when the eye was still firm. Once again there was more than one method to choose from including corneal relaxing incisions. However the technique popularised by Maloney (William), using paired perpendicular keratotomies (PPK) on the steep meridian at the 6mm OZ, later known as TAK (transverse astigmatic keratotomy), migrated more peripherally to the limbus as limbal relaxing incisions (LRI) became common when popularized in recent times by the **Nichamin (Louis "Skip")** Nomogram.

Performing tangential incisions at the time of cataract surgery was much less reliable compared to performing these incisions later, as a secondary event, despite being less frequently applied in this manner. The reason for this anomaly was not immediately obvious, but became apparent when it was discovered that temporal incisions, which are astigmatically active even down to 2.2mm **(Figure 1)** caused a shift in the existing astigmatism **(Figure 2)** magnitude and orientation as soon as it was performed. If this phenomenon was not taken into account, either for LRI's or toric implants, then the placement of the treatments must be 'off' both in magnitude and more importantly axis, resulting in rotational shifts of the existing astigmatism that are usually uncontrolled.



Deg.	F/S Mean	#
0	0.28 F	140
15	0.13 F	52
30	0.19 F	28
45		0
60	0.51 F	12
75	0.26 F	17
90	0.49 F	86
105	0.43 F	19
120	0.62 F	21
135	0.22 S	3
150	0.05 F	20
165	0.58 F	8
180	0.39 F	139
195	0.37 F	59
210	0.28 F	28

The mean flattening or steepening is shown scaled such that from the centre of the pupil to the angle marker is 1.00 D. Arrows indicate flattening (towards the pupil) or steepening (away from pupil). The

Mean Flattening = 0.34 D

n = 642

Measurement Type
● Keratometry
○ Topography
○ Refractive

Data
● Flattening/Steepening
○ Torque
○ Angle of Error

Spacing (degrees)
○ 5
○ 10
● 15
○ 20
○ 30
○ 45

Scale
○ 0.5 D
● 1 D
○ 2 D
○ 3 D
○ 4 D
○ 10 D

Means
● Arithmetic
○ Absolute

Figure 1: Flattening/steepening effect using 2.2 mm incision by keratometry 1 month post-op. The arrows pointing to the centre of the eye indicate flattening and the numbers around the eye the number of cases at the particular meridian. The table displays the mean magnitude of flattening or steepening.

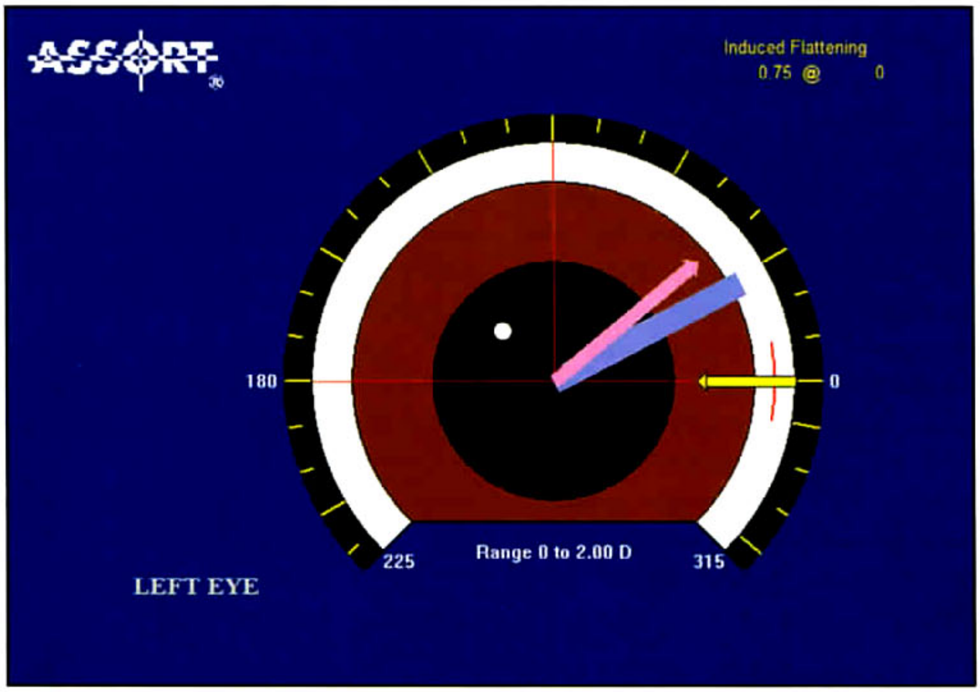


Figure 2: The intended temporal incisional meridian (phaco) in many cases may differ to the steepest corneal meridian at 30 degrees and hence reduce the flattening effect at the steepest preoperative meridian and rotate it away from the incision to 41 degrees.

An effective analysis will show all phaco incisions likely have astigmatic activity, these trends being clearly evident even with bimanual incisions and phaco when vectorially examined. 30, 31 Many cataract surgeons accept this phenomenon and usefully place the phaco incision at the steepest corneal meridian, thus gaining 0.5D or more of flattening effect and astigmatic reduction without any other intervention. LRI's are placed as a pair conventionally on either side of the cornea with a third temporal phaco incision. This practice might be counterproductive to the goal of astigmatic reduction, directing that even longer LRI's could be necessarily employed. The technique I employ for LRI's requires only one at the opposite side to the "on axis" phaco incision. It can reduce corneal astigmatism by up to 2.0D requiring only one extra (LRI) incision. A further advantage is dispensing with the need of complicated, uncertain adjustments for an "off axis" temporal phaco incision.

This way the paradigm does not necessarily require toric implants until 2.0D or more of corneal astigmatism exists. Fitting is **Richard Troutman's** observation from his contribution title ***"Quest for Sphericity"***, that may suggest there would be a benefit for quality of vision for the light to pass through a spherical cornea and a spherical implant with less likely aberrations than light passing to the macula deviating on its way through two astigmatic surfaces - the cornea and the implant.

As a result of heightened expectations in patient outcomes in cataract surgery, the philosophy has naturally become refractive and the goal has shifted from one of astigmatic neutrality to astigmatic reduction. As a general rule the larger and more central the incision and the less the amount of suturing, the greater the effect. In this way the cataract surgeon has come to examine the preoperative and targeted astigmatism prior to surgery. This has become more compelling with the advent of limbal relaxing incisions and toric implants to reduce patients' astigmatism at the time of cataract surgery.

At this time toric implants are becoming more available in higher astigmatic powers, as well as wider ranges of spherical powers. These are becoming valuable additions to our surgical armamentarium, but are also under the same constraints of variability of phaco incisional behavior, and the adjustments usually required for all temporal incisions. An effective vectorial analysis is also required after toric implant surgery to determine the angle of error, to direct what might be done with the implant soon after the cataract surgery to reduce excess remaining refractive astigmatism.

Comparing Pre and Post Astigmatism Values in Magnitude

Most would agree that comparing preoperative and postoperative astigmatism magnitude alone would not identify the separate "errors" of magnitude and axis. To perfect techniques of astigmatism surgery and determine whether patient factors, surgical technique or instrument error might be responsible, separate means of analysing magnitude and axes were required and should not be limited to the polar axes alone.

The Alpins method provides the ability to separately compare the magnitudes and axes of astigmatic change (using vectors), where changes in astigmatism are planned or have occurred. This has allowed for the magnitude of error (actual correction minus intended correction), angle of error (the angle described by the vectors of the achieved correction verses the intended correction) and difference vector (how far you miss the target; *which determines the magnitude and axis required to correct any remaining astigmatism to the initial target)*. Hence, means and standard deviations could be determined and differences between eyes and techniques compared. [2] The key element of this technique, which had not been addressed in previous analysis techniques, was the identification and quantification of the non zero targets that were prevalent in astigmatism treatment due to the different corneal and refractive methods of measuring astigmatism.

Targeting zero at corneal or refractive, but not both where differences exist, had become problematic and unachievable for patients. A useful benefit of the Alpins method of astigmatic analysis is its ability to perform an analysis for both corneal and refractive measurements. The treatment, referred to as the target induced astigmatism vector (TIA) is a constant and links these different types of analyses whether the surgical induced astigmatism vector (SIA) is determined by manifest, wavefront or cycloplegic refractive parameters, or by topographic or keratometric corneal parameters. [21]

Almost too obvious to state, the existing maxim has evolved "if you don't know where the target is, how can you know how much you have missed it by" The Alpins Method readily explained the corneal and refractive changes occurring after astigmatic surgery and quantified whether too much or too little treatment was applied and, whether the treatment was on-axis or off-axis. This vector analysis approach to examine regular and irregular astigmatism is best understood using the analogy of a golf putt. [32]

This practical golf analogy simplified this method of astigmatism analysis by demonstrating the failure to achieve surgery success is based on two factors: Firstly, whether the ball was hit too hard or too soft? And secondly, whether the putt (treatment) was "on axis" and if not, was the "off axis" direction the ball was hit to the right or left - being clockwise or counter clockwise? The fundamental concepts of this method are demonstrated below using the golf putt analogy. For our purposes, a golf putt is a vector possessing magnitude (length) and axis (direction).

Figure 3a displays the preoperative astigmatism, a non-zero target and the postoperative astigmatism. The *intended* change in preoperative astigmatism the surgeon is attempting is the intended putt (the path from the ball to the hole), known as the target induced astigmatism vector (TIA) **(Figure 3b)**. It is important to note the surgeon is attempting to reduce all the astigmatism in this case. The amount of change in astigmatism the surgeon actually induces corresponds to

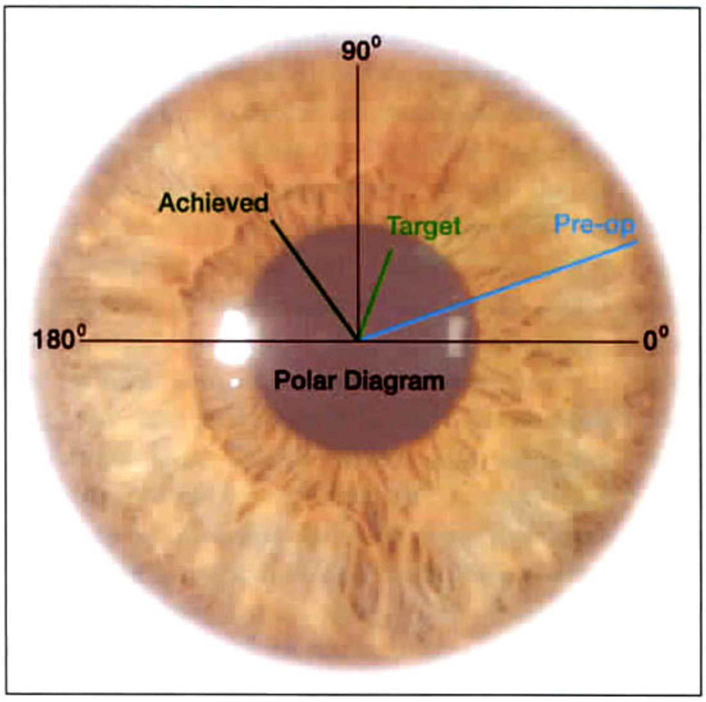
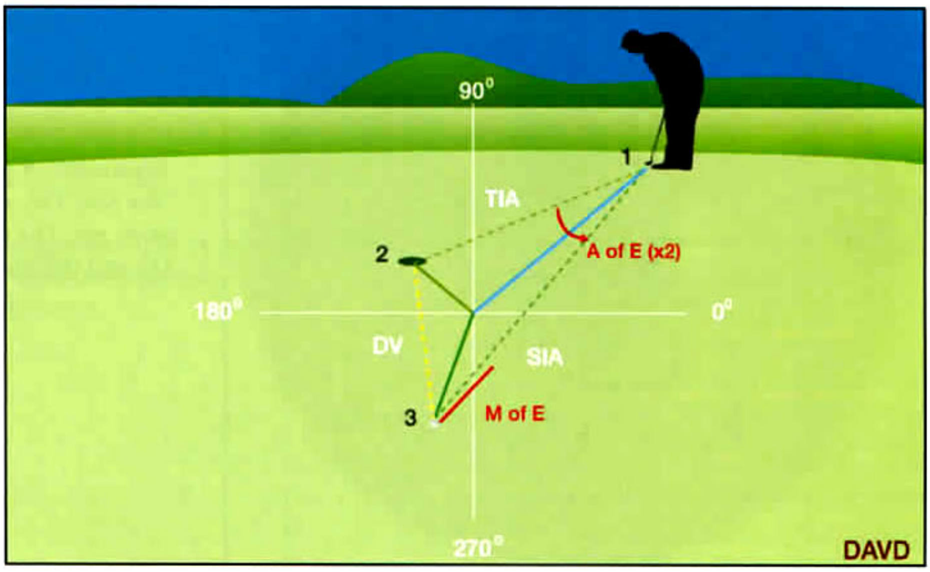


Figure 3A: Polar diagram displaying the pre and post operative astigmatism and a non-zero target.

Figure 3B: Vector mapping of a golf putt equivalent to a DAVD demonstrates the Alpins approach to astigmatism analysis. 1 represents the preoperative astigmatism, 2 the target and 3 the postoperative astigmatism in continuous lines.



the surgically induced astigmatism vector (SIA), which represents the putt's *actual* path. The putting green represents the vectorial analysis on a double angle vector diagram (DAVD). For all intents, it is flat without any wind interference.

If the ball misses the target on first attempt, then the second putt's distance away and direction to the hole corresponds to the difference vector (DV). In other words, this demonstrates the error in achieving the attempted correction of astigmatism and tells us how far we missed the target effect. The distance of the second putt to the hole represents an absolute measure of the success of the first putt. Then the smaller the number the more successful the first putt, and if the ball ended up in the hole on the first putt this would indicate a zero difference vector. However, if two golfers were on the green and both ended up at the same distance from the cup for their second putt then the more successful shot would be the one in which the first putt was furthest from the cup. This measure of relative success equates to the Index of Success (IOS) and is calculated by dividing the DV with the TIA, or the length of the second putt compared to the length of first attempted putt.

To utilise the mathematics effectively, the polar co-ordinates need to be converted to rectangular (or Cartesian) co-ordinates using a double angle vector diagram (DAVD). In a DAVD the axes of the vectors are doubled but the magnitude remains unchanged, simplifying analysis and interpretation of astigmatic values and surgical vector calculations. The axes of the vectors are then halved to display how they would appear on an eye **(Figure 3c)**.

Note that vectors represent a steepening in a particular direction. Although vectors share the same units as astigmatism, i.e. dioptres and degrees, they have different fundamental properties since they can only be calculated and cannot be measured. Astigmatism can be directly measured by corneal or refractive means.

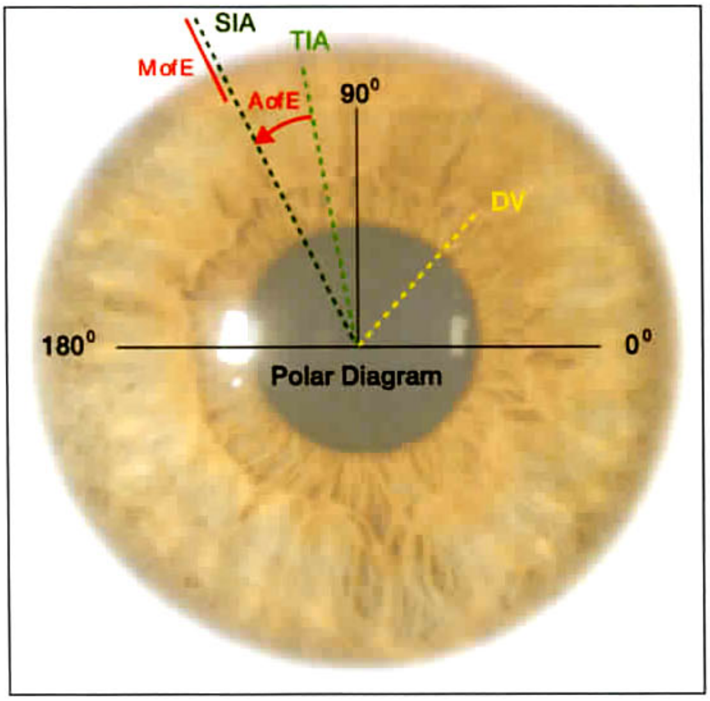


Figure 3C: A polar diagram displaying how the SIA, TIA and DV vectors would appear on an eye. The direction of the Angle of Error (AE) and the Magnitude of Error (ME) are also displayed.

The actual or surgical induced astigmatism (SIA) change quantifies the change the surgeon actually induces. This became a vital concern as laser treatment analyses have been traditionally performed using refractive parameters and incisional surgery analyses using corneal parameters.

Further, to describe if the ball was hit too hard or too soft, the Correction Index (CI) is calculated by dividing the SIA (actual surgical effect) with the TIA (intended targeted change) and would ideally be 1.0. If the ball was hit too hard it would be greater than 1.0, resulting in an overcorrection in the astigmatic treatment. In like manner, if the ball was hit too soft it would be less than 1.0, resulting in an undercorrection of the intended astigmatic treatment.

The amount and the various relationships between the TIA, SIA and DV has come to be known as the Alpins method of astigmatism analysis. The "hole in golf putting" analogy was not necessarily at the zero point of a graph but could have a magnitude and associated orientation. The value of this method is in its application for traditional forms of statistical analysis, its ability to compare the relative success of various surgical procedures and its comprehensive set of principles for astigmatism analysis expanding capabilities to corneal as well as refractive means.

Performing analyses based on refractive outcomes alone limited future adjustments in technique and nomograms. Analysing corneal astigmatism in parallel, in addition to refractive astigmatism after a procedure would allow for a better understanding and certainty of what actually occurred during surgery. For example, this may occur when the postoperative astigmatism magnitude is similar to the preoperative by refraction. Gravely, the surgeon will assume there was minimal subjective effect on astigmatism when in fact the objective measurement of the cornea may show a significant actual change. For this reason, comprehensive astigmatic analysis by both corneal and refractive parameters is mandatory.

For a comprehensive astigmatic analysis it is important to know the effect of the induced astigmatism (SIA) projected along the intended direction (TIA), which is known as the Flattening Effect (FE). [22, 23] This effect can be calculated using the formula SIA x Cosine (2 x AE) as displayed in **Figure 4**. The effect of the SIA at the

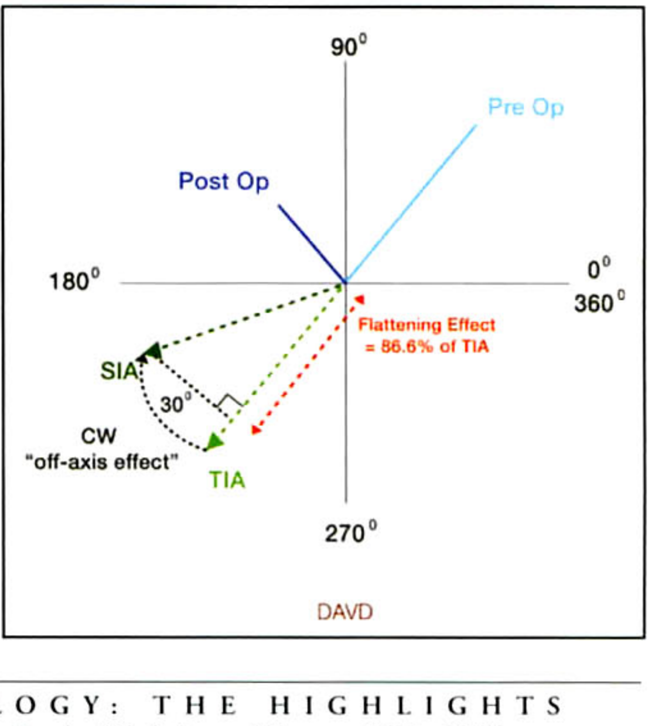


Figure 4: Calculation of Flattening Effect (FE) at the incision meridian using trigonometric principles. CW = clockwise direction.

intended meridian can be calculated by dropping a perpendicular line from the SIA to the TIA, and subsequently determining if there was a flattening or steepening effect along the intended meridian and its magnitude. This can be done using corneal or refractive parameters and incisional or refractive laser surgery.

When the astigmatism measured on the cornea preoperatively differs in direction to the refractive astigmatism, then planning "on axis" surgery on refractive astigmatism will be off-axis for corneal and vice versa. Relating this back to the golf analogy discussed earlier, means the goal of the surgery may not in fact achieve a full correction of astigmatism to zero, indicating that the target is placed elsewhere, at another non-zero target point. It is crucial that the surgeon understands that any astigmatic analysis indicating the success of the treatment be related to this non-zero target created by the imperfections in the eye's astigmatic status, and not zero, which might be desirable but not feasible. An example of this relates to toric implants where the lens used may not correct all the preoperative astigmatism. In such a case, the best scenario is based on the amount the surgeon *intends* to correct rather than what they would wish to correct determined by the corneal astigmatism and its meridian. The refractive astigmatism amount and its axis are not determinable because of the cataract and the removal of any lenticular astigmatism with the cataract.

Figure 1 shows the mean flattening of various 2.2mm phaco incisions around both right and left eyes using pre and postoperative keratometry readings one month postop. Calculating the mean flattening (or steepening in some cases) effect in a series of incisional procedures allows the surgeon to gauge the effect of his or her incisions at different meridia around the eye, as well as the varying effect of different incision sizes and placements. This can be used in future surgeries to predict the amount of astigmatism reduced using the phaco incision as a tool. Moving the incision around the eye to the steepest corneal meridian is the most effective means for maximising the reduction of astigmatism and harnessing the characteristics of a particular incision to reduce corneal astigmatism existing prior to cataract surgery. Using the Flattening Index (FI) can further quantify the flattening effect for a group of eyes, calculated by dividing the flattening effect by the TIA where the FI like the CI is preferably 1.0. [21]

Calculating the "off axis" effect of a phaco incision is most useful in cataract surgery where the intended incisional meridian may be routinely temporal and does not necessarily coincide with the steepest corneal meridian oriented elsewhere on the cornea **(Figure 2)**.

Other terms of use in astigmatism analysis using The Alpins Method is displayed in a polar diagram **(Figure 5)**. Here, we are concerned with the angle of error (A of E), which is the angle described by the vectors of the actual correction (SIA) versus the intended correction (TIA). The A of E is positive if the achieved correction is counter clockwise and negative if clockwise to its intended. **Figure 4** also demonstrates the magnitude of error (M of E), being the arithmetic difference between the SIA and the TIA. The M of E is positive for overcorrections and negative for undercorrections. Adjusting nomograms based on past experience is most effectively done using the inverse of the CI (correction index), which is Co-efficient of adjustment (C of A), which represents dividing the TIA by the SIA and is preferably 1.0. [21]

In addition, these vector analysis tools allow us to determine what proportion of the treatment was useful in reducing astigmatism. They also render how much of the surgically induced astigmatism (SIA) resulted in undesired rotation of existing astigmatism described as torque,

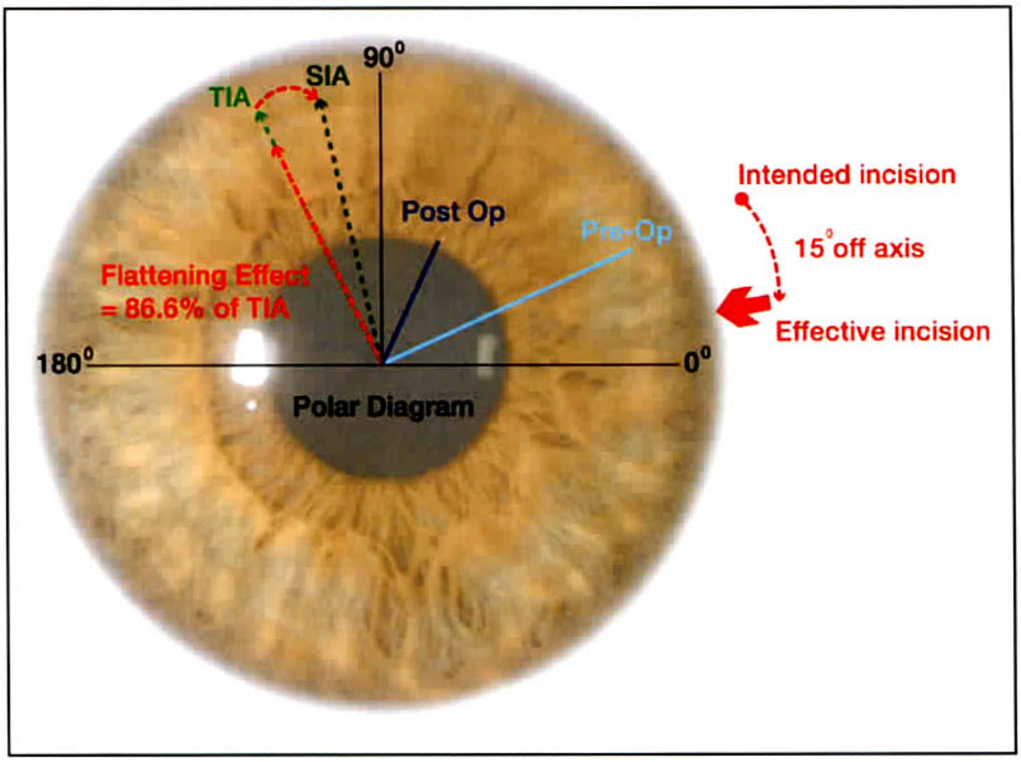


Figure 5: A polar diagram derived form figure 4 displaying the Flattening Effect (FE) and the CW direction of the Angle of Error (AE) as they would appear on an eye. The AE displays where the effective incision occurred relative to the intended incision at the steepest meridian.

introduced with this technique and explained below. The refinement of nomogram calculations for future treatments can then be effectively reported. A substantial part of this technique was adopted by the Astigmatism Project Group as recommendations of the American National Standards Institute as a standard reference for astigmatic refractive error analysis for laser system evaluation. [33, 34, 35]

Misaligned Astigmatic Treatment

Any loss of effect (flattening or steepening) at the intended axis or meridian results in rotation of the astigmatism orientation and is known as torque. [22, 23] This orientation shift lies 45 degrees clockwise or counter clockwise to the steep astigmatism meridian **(Figure 6)**. To avoid misunderstanding, anytime a loss of astigmatic effect is discussed it must be related to a reference axis which is usually the meridian (or axis) the surgeon is attempting to flatten (or steepen). Many speakers and articles, particularly with the release of toric intraocular lenses overestimate the loss of flattening effect when the astigmatic treatment is misaligned. This is based on a near linear relationship between the failure to reduce astigmatism magnitude and misalignment, employing comparisons between postoperative and preoperative astigmatism parameters without considering axis. [22]

Vector analysis, however, indicates that at 15 degrees off-axis, 13.4% of the flattening effect is lost **(Figures 4 and 7)**. A frequent suggestion and a severe overestimation is that 50% of the effect is lost at 15 degrees off-axis. Vector analysis indicates that treatment (ablative or incisional)

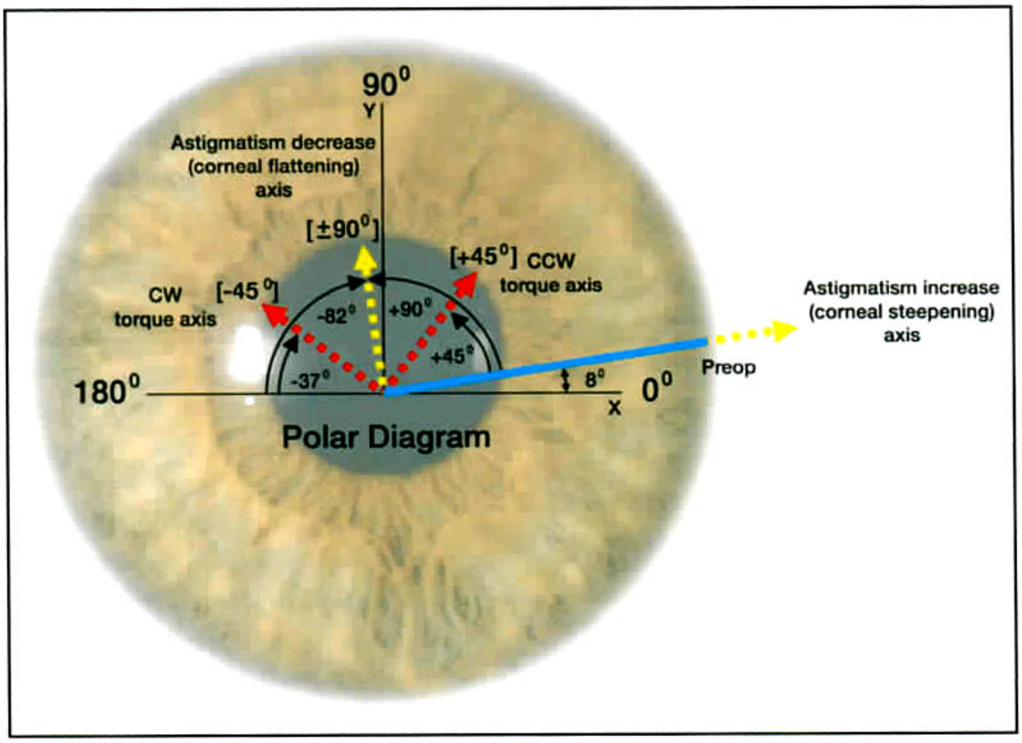


Figure 6: The principal meridians of flattening, steepening, CW and CCW torque in a polar diagram as they would appear on an eye. Note the steepening at the Preop meridian when the SIA coincides with that meridian.

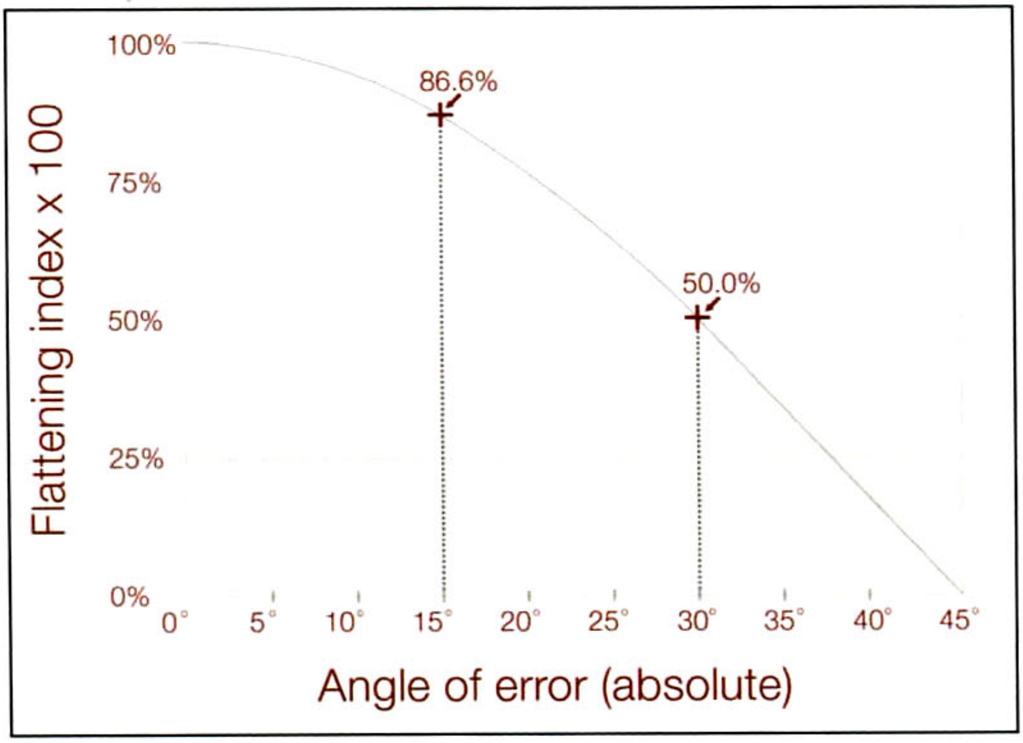


Figure 7: The reduction in flattening effect versus increasing misalignment of astigmatism treatment. Note the SIA = TIA so that there is no over or undercorrection occurring.

would need to be 30 degrees off-axis to yield a 50% loss of effect. [22] As the flattening effect of the SIA at the intended meridian diminishes, the torque (or rotation effect) increases; in effect, rotating the preoperative astigmatism around. At 45 degrees misalignment there is no flattening effect of the SIA at the intended meridian and all the effect of the SIA is going into rotating the preoperative astigmatism (torque). Beyond 45 degrees misalignment there is an increasing steepening effect so the amount of astigmatism postoperatively, is greater than preoperatively at the intended meridian. Performing a keratometry measurement at the intended meridian before and after the surgery would physically demonstrate this loss of effect of astigmatism reduction at the reference axis – in this case the treatment axis.

Treatment Based on Corneal Versus Refractive Parameters

It was also in the early 90s that a conundrum existed where corneal surgeons with AK incision frequently targeted a spherical cornea and refractive surgeons with photoastigmatic refractive keratometry (PARK) routinely targeted a spherical refraction, resulting in two different treatment paradigms for one astigmatic concern.[20]

A non-zero goal was an inevitable consequence with astigmatism remaining on the cornea or in the refraction, in cases where the astigmatic magnitude and/or the axis differed between the two approaches. In excimer laser surgery a non-zero astigmatic target was planned for on the cornea, and in astigmatic keratotomy the emphasis to reduce astigmatism was placed on the cornea, and hence refractive cylinder would inevitably remain in the spectacles, [20] just as it can with hard contact lens fittings.

The surgeon now had a decision to make. Would the emphasis be given to spectacle or corneal astigmatism as treatment parameters? This became of particular concern with the introduction of topography into the clinical setting, where topographically guided paradigms aimed to sphericise the cornea. Pioneers of astigmatic keratotomy such as **Richard Troutman**, **Spencer Thornton**, **Kurt Buzzard** and **John Gayton** advocated placement of incisions on the steepest (positive) corneal meridian. **Troutman**[12] specifically noted the importance of corneal topography to correct astigmatism. Less frequently, others such as **Casebeer** [14] and **Villasenor** [15] suggested placing the incisions on the steepest refractive meridian, as did medical investigators for laser manufacturers.

In the majority of cases, however, the refractive astigmatism would not match the corneal astigmatism in magnitude, axis, or both. A systematic method to link both refractive and corneal parameters would require utilising vector planning, as treatment based solely on corneal parameters would result in some astigmatism remaining in the refraction and vice versa. In an ideal situation the refractive and corneal astigmatism would always be identical in both magnitude and orientation, rendering this potential conflict irrelevant. However, for the more frequent scenario this is not the case. Then, calculating the minimum amount of astigmatism that can be achieved for the eye by treatment prior to surgery must be a priority to avoid adverse clinical outcomes.

The difference between corneal and refractive parameters is common because of the astigmatism mode being measured and the differing tools that measure them. Topography and keratometry measure the corneal shape alone resulting in an objective measurement. Whereas a manifest refraction results from the entire visual system, from the front corneal surface all the way back to include the visual cortex of the brain, so astigmatism here can be influenced at many interfaces including non optical perceptual components. This is a perfect case in point for the need for additional inclusive astigmatism analysis to our existing tools of evaluation.

Another valuable tool in The Alpins Method is the *Ocular Residual Astigmatism* (ORA), which describes the vectorial difference between the refractive and corneal astigmatism. [20-29] It has been known by various inadequate descriptive titles which include non corneal, intraocular and lenticular astigmatism and is an effective means of quantifying internal ocular aberrations.

Calculation of ORA

The ORA is determined by calculating the vectorial difference between, on the one hand, wavefront or manifest refraction measurements for refractive cylinder, and on the other, topography or keratometry measurements for corneal astigmatism **(Figure 8a).** Doubling the axes of the astigmatism whilst leaving the magnitudes unchanged allows for the conversion of polar co-ordinates to rectangular co-ordinates **(Figure 8b).** The ORA being a vector quantity connecting the two astigmatisms from cornea to refractive on this mathematical construct, is then transferred to the origin (x=0, y=0) and halved to simulate how it would exist within the eye (**Figure 8c** – polar diagram). This vectorial difference, measured in diopters and degrees and calculated using basic trigonometric principles, has a proportional relationship with astigmatism. As the astigmatic differences between refractive and corneal astigmatism increases, so too increases the magnitude of the ORA, in either amount or angular separation. Therefore, the amount of remaining postoperative astigmatism in the ocular system that cannot be eliminated will also inevitably be greater. Treatment using refractive parameters alone neutralise the internal ocular astigmatism quantified by the ORA on the front corneal surface, leading to increased aberrations and a reduction in the quality of vision achieved. [29]

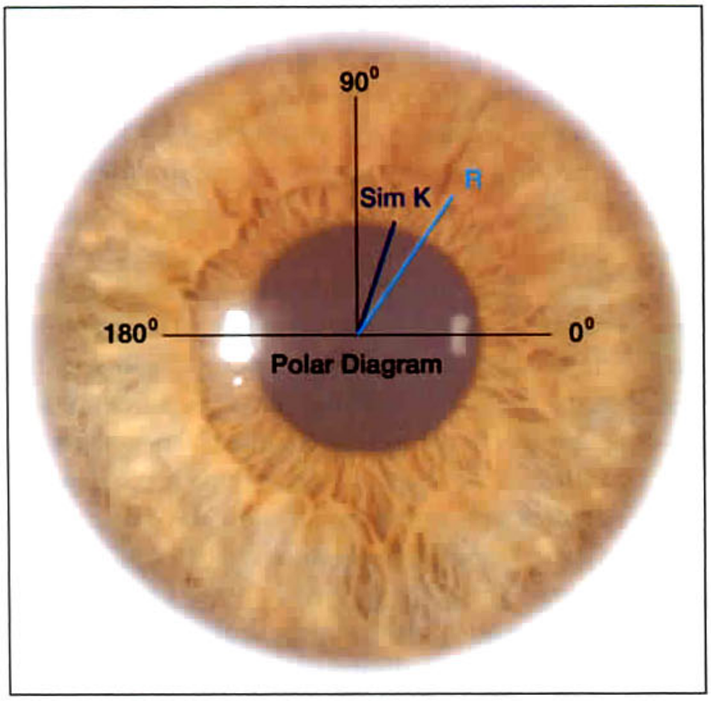


Figure 8A: Polar diagram of refractive cylinder at positive axis and simulated keratometry.

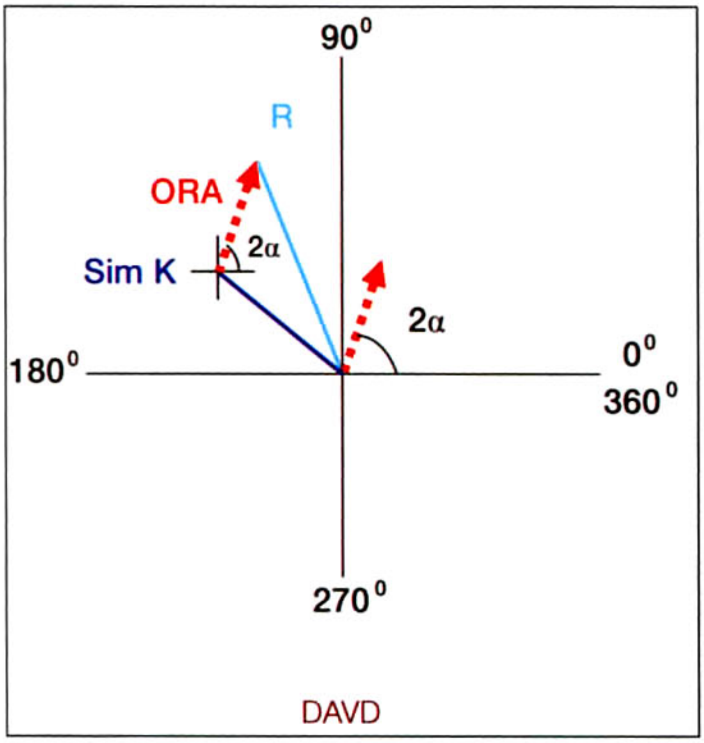
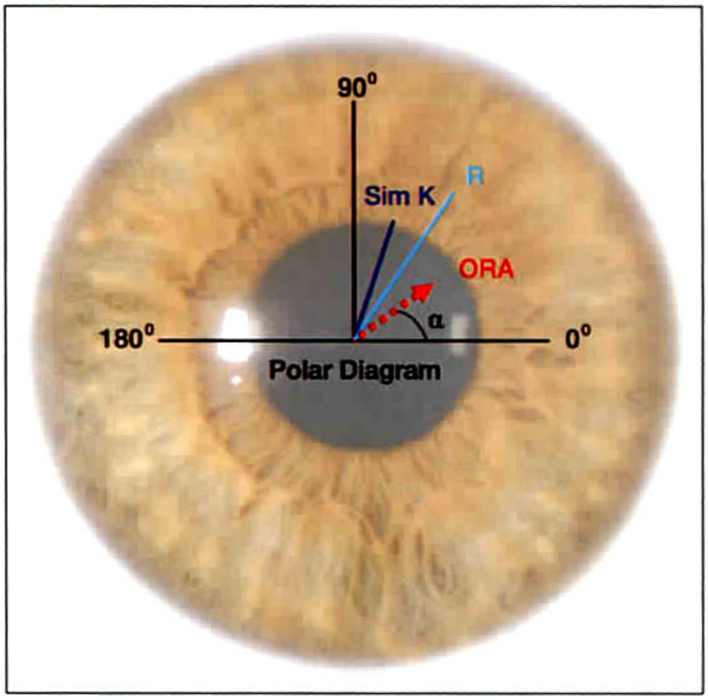


Figure 8B: DAVD showing a 'doubling' of the axes without a change in the astigmatic magnitudes.

Figure 8C: Polar diagram displaying the ORA as it would appear within the eye.



A proportion of patients' dissatisfied with their laser vision correction outcome likely include this group with an excess amount of remaining corneal astigmatism and consequent excess ocular aberrations. However, utilising The Alpins Method by determining a patient's ORA routinely as part of the preoperative preparation, allows the surgeon to predict potential adverse outcomes prior to refractive surgery. This would then determine how best to distribute the neutralisation of the ORA between the cornea and the refraction in an optimised manner using vector planning.

Treating by refractive (manifest or wavefront) parameters alone, as is customarily the case in refractive laser surgery will leave the ORA wholly targeted for the cornea **(Figure 9a)**. Whereas treating by corneal values alone in like terms to wearing a spherical surface hard contact lens will leave all the ORA (residual astigmatism) in the refraction **(Figure 9b)** [36] . Optimal treatment using vector planning looks at combining both preoperative parameters in the treatment plan and placing more emphasis on the elimination of corneal astigmatism, the more 'unfavourable' the orientation of what is expected to remain **(Figure 9c)**. In general, with-the-rule is more favourable than against-the-rule and oblique astigmatism is more unfavourable yet again. As **Sawusch** and **Guyton** explained in 1991 [37], two basic principles apply in determining the emphasis on corneal parameters in the treatment plan. One being less corneal astigmatism is preferable to more. **Seiler** et al demonstrated an increase in spherical aberration associated with larger amounts of corneal astigmatism,[38] the other maintaining the remaining astigmatism should be with-the-rule (Javal's rule[39]) for distance vision. Placing the clearest image in the vertical meridian improves visual acuity for distance, as measured by a Snellen chart which contains more vertical elements than horizontal. [40]

The technique of vector planning can reduce a greater amount of corneal astigmatism than treatment using refractive parameters alone,

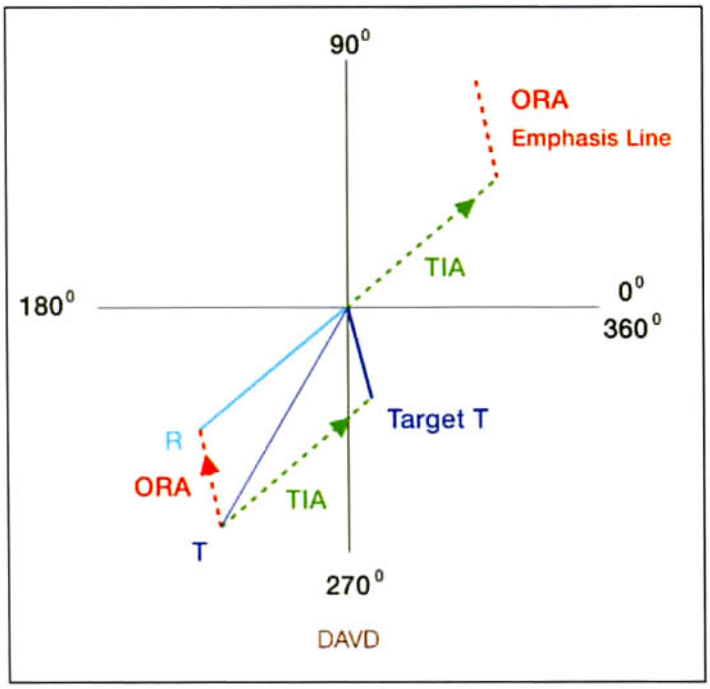
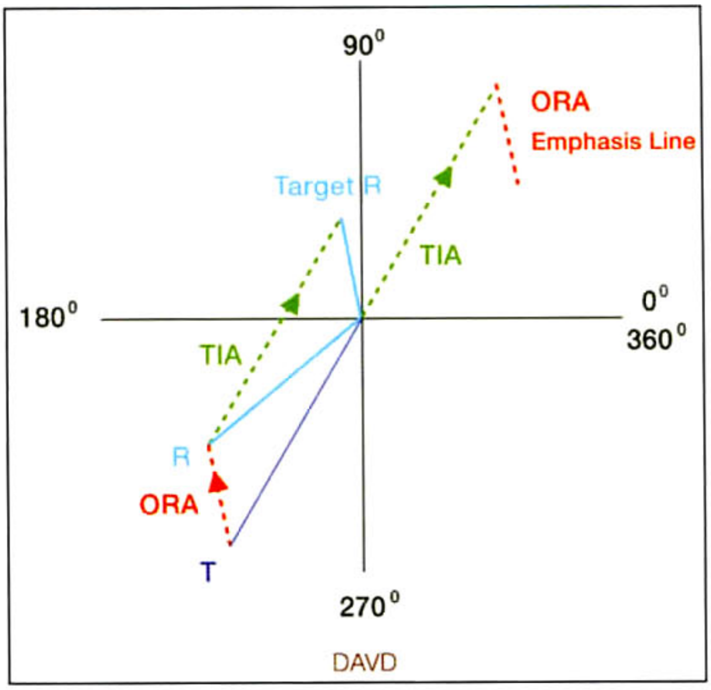


Figure 9A: Double angle vector diagram of treatment by refractive values to achieve a spherical refraction. The emphasis line displays the treatment based on 100% refractive parameters.

Figure 9B: Double angle vector diagram of treatment by topographical values to achieve a spherical cornea. The emphasis line displays the treatment based on 100% topographic parameters.



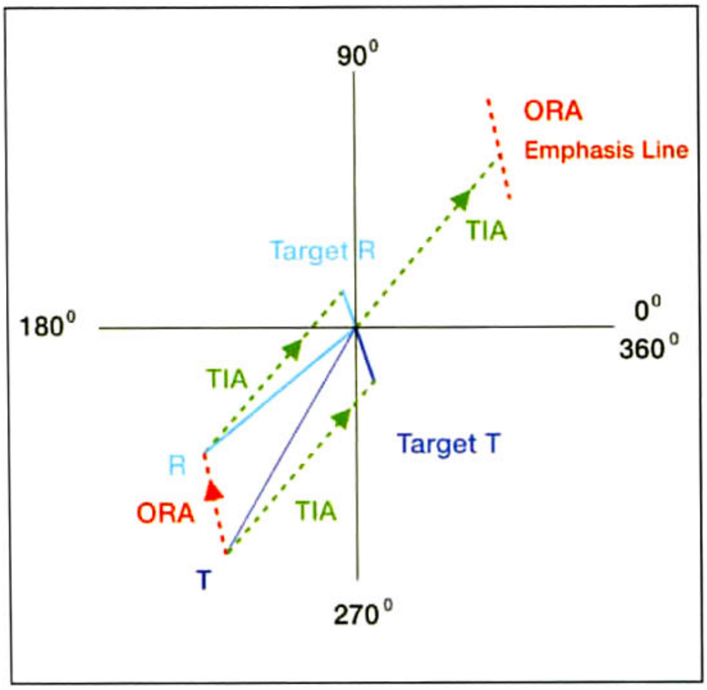


Figure 9C: Double angle vector diagram using both topographical and refractive astigmatism values to optimise the treatment.

and as a result fewer second and third order aberrations would remain. [28, 29] Alternatively, topography-guided treatments, which are typically used to treat irregular corneas after previous corneal surgery, may induce higher-order aberrations leaving excess refractive cylinder in the manifest refraction.

Using this method of vector planning, the surgeon can combine the corneal astigmatism parameters into the refractive treatment plan, with a selection of 99 different additional emphasis percentage points with which to distribute the ORA neutralisation away from either extremes of completely 100 % corneal or 100% refractive parameters alone.

Although wavefront-customized treatments offer many benefits to our patients over manifest refraction, wavefront refraction alone does not entirely treat astigmatism where the ORA is significant. In a previous study 20 this was shown to be more than 1.00D in 34% of eyes treated for astigmatism in association with myopia. In addition, this study demonstrated 7% of eyes would be targeting more corneal astigmatism than was present before surgery was undertaken.

Outcomes Using Combined Topographic and Refractive Parameters to Optimally Treat Astigmatism

At the completion of the laser vision correction process, where the targeted spherical equivalent is zero, the patient is free of spectacles, but must view the world through their cornea for the rest of their lives. The old adage "less is more" certainly applies in the world of astigmatism, necessitating the importance of the ORA to the cornea. As surgeons, the cornea and how much astigmatism remains on it is our primary responsibility.

It is important to highlight that no matter what the percentage chosen on the 'emphasis' bar, the minimum amount of total astigmatism (corneal *plus* refractive), equal to the ORA, is being targeted at every point on the percentage scale **(Figure 9c).** If the combined magnitude of the remaining astigmatism (corneal *plus* refractive) is greater than the initial ORA, the surgery then fails to achieve the maximum astigmatism treatment and is undesirable.

Even though all the astigmatism is not correctable from the visual system, results with this technique were still significantly better than they would have been using conventional refractive astigmatism values alone. This has been demonstrated in several studies [28, 29] together with improvement in visual outcomes with no increase in refractive cylinder outcomes as would theoretically be expected. In addition, this reduction in corneal astigmatism remaining, compared with treating using refractive parameters alone, displayed a reduction in ocular aberrations and a greater potential for improvement in BCVA. I personally have routinely treated more than ten thousand astigmatic eyes in this manner since 1993.

A recent study[28] of the treatment of myopic astigmatism using photoastigmatic refractive keratectomy and vector planning in forme fruste and subclinical keratoconus patients showed that, on average, we were able to reduce the corneal cylinder by an additional 0.68D, compared to results that would have theoretically been attained by treating refractive values alone. This was achievable without compromising the refractive outcome.

It is extremely unlikely that treatment of irregular corneas as a result of keratoconus, can achieve universally excellent outcomes without the inclusion of corneal parameters in the treatment plan. The results achieved demonstrated the importance and effectiveness of addressing the corneal shape in the treatment. The omission of this facility by using manifest or wavefront parameters alone is likely to leave a significant percentage of eyes with excess corneal astigmatism, and consequently elevated higher order aberrations leading to some less than satisfactory outcomes. These adverse refractive outcomes have led to many advocating against treating patients with forme fruste and mild keratoconus with ablative laser vision correction techniques.

Another study[29] looked at treating myopic astigmatism in two groups with normal corneas: one with wavefront treatment alone and the other using wavefront combined with vector planning. The WF&VP combined group displayed a greater reduction of corneal astigmatism, less increase in HOAs and better visual outcomes under mesopic (LCVA and HCVA) conditions compared to the WF alone group.

By using vector planning techniques we are gaining something for nothing, effectively achieving less corneal astigmatism without an equivalent penalty of excess refractive astigmatism.

Spherical Shifts and Corneal Coupling

With any treatment of astigmatism it is important to note the subsequent effect on the sphere. Coupling refers to the associated spherical change that can occur when there is an astigmatic change. The amount of spherical shift, which can be either myopic or hyperopic depending on the associated sphere, can vary according to the surgical procedure.

Consider a keratometry reading of 44.00D/46.00D – this would have an average of 45.00D. A coupling of 0% would result in 44.00D/44.00D. Here the spherical equivalent is reduced by half the power of the cylinder. Such a result would occur in myopic astigmatism ablative surgery. **Richard Troutman** has described this as 2:2 ratio. Following on from above, there is 2D spherical change for 2D astigmatic reduction as measured from the steepest corneal meridian. For hyperopic astigmatism a coupling of 0% would result in 46.00/46.00.

In contrast, employing incisional techniques such as Astigmatic Keratotomy would result in 45.00D/45.00D, equaling 100% coupling. Troutman has termed this a 2:1 ratio. In effect, a 1D sphere change for every 2D astigmatic reduction from the steepest corneal meridian, adding one half of the cylinder power to the underlying spherical power resulting in an unchanged spherical equivalent.

Treatment Ablation Profiles for Irregular Astigmatism

The method of vector planning can be utilised for both regular and irregular astigmatism. This technique can be expanded upon to reduce and regularise asymmetric and non-orthogonal bow-tie patterns measured by topography in cases of irregular astigmatism. Just as it is prevalent for the refractive astigmatism to differ in magnitude and/or axis from the corneal astigmatism, so it is for the two steepest astigmatism meridians of the opposite semi-meridians of the cornea to vary in magnitude and/or orthogonal meridia from each other.

An excimer laser ablation algorithm can be calculated based on asymmetrical surgical treatment using vector planning, and applied to non-orthogonal and/or asymmetrical differences in astigmatism between the superior and inferior semi-meridians of the cornea. This vector planning technique can achieve any desired corneal shape to improve visual outcomes in cases of irregular astigmatism.

The treatment paradigms for irregular corneas using photoastigmatic refractive keratectomy (PARK) in previous studies have included decentred ablations over the cone in patients with keratoconus[41]. Treatments based entirely on corneal parameters such as computer assisted videokeratography (CAVK) [42] and most commonly, ablations centred on the pupil dependent exclusively on manifest refraction. [43, 44] The visual outcomes of these studies have shown only a partial decrease in refractive astigmatism and in some cases an increase in the corneal irregularity. [42, 44, 45] In those studies 23 where the corneal astigmatism was reported post-operatively, there was still a significant amount remaining on this principal refractive surface which impacted adversely on the unaided visual acuity results. Due to the irregular shape of the cornea in these patients, a larger ORA occurred than would be expected in normal eyes. [28, 46]

Recognising and addressing differences between the corneal shape (topography) and the visual function (refraction) is an essential step to realising the maximum potential vision for an astigmatic eye. If a relatively high ORA has been calculated for a particular case (e.g. 2.20D), it is important the surgeon and patient understand that the outcome may be less than ideal due to this uncorrectable amount of astigmatism remaining in the visual system of the eye postoperatively; especially if the case is wholly destined for the cornea. No matter how accurate or successful the surgery, the ORA is the amount of astigmatism that will remain in the optical system of the eye due to these unavoidable differences between refractive and corneal astigmatism. If the ORA indicates a significant amount of astigmatism will remain in the system relative to the preoperative amount, the patient may be advised against refractive laser surgery. This could avoid frustration amongst patients who have been treated by laser vision correction for astigmatism. [46]

Limitations of Simulated Keratometry Values by Topography

The simulated keratometry is a best-fit value or mean achieved over a number of measured constant reference points of the topography map. Variations exist in the dioptric magnitude and orientation of the astigmatism on each of the two halves, called semi-meridians, of the cornea. There may also be a non-orthogonal relationship between the two astigmatism values.

The orientation of the simulated keratometry can be determined in many cases using any one of three axes on the same cornea: an orientation aligned with either one of the two non-orthogonal hemi meridians or another intersecting between the two. A more accurate approach would be to divide the cornea into two equal halves (semi-meridians) and determine the flattest and steepest meridian for each half. In our experience the power measured by topography in the 5mm zone of the cornea displays a more accurate description of the overall shape of the cornea than either the 3mm or 7mm zones.

Quantifying Irregular Astigmatism

No studies have reported the outcomes in corneal irregularity after excimer laser treatment on virgin irregular corneas due to idiopathic causes, despite a substantial amount of information obtained from topographers and aberrometers and numerous studies on the improved outcomes using wavefront based or topography-guided treatments. Perhaps this is due to some uncertainty in how the corneal irregularity can be accurately quantified.

The condition of corneal irregular astigmatism can be precisely quantified in diopters (D) as the topographic disparity (TD).[47-49] The TD is calculated as the dioptric distance between the displays of superior and inferior topographical dioptric values on a 720 degree double-angle vector diagram (DAVD). The TD quantifies both the non-orthogonal and asymmetrical component of corneal irregularity as a single dioptic magnitude value with an axis. As a vectorial value it is an exact convenient way of assessing the variable of irregularity.

There is a direct proportional relationship between increasing ORA and TD; the greater the topographic disparity the greater the ORA. [47] It is therefore of utmost importance when treating irregular corneas, that the topography values for astigmatism be incorporated into the treatment plan, as treatment based on the manifest refraction or the wavefront aberrometry cylinder alone can leave the cornea with excess avoidable astigmatism as discussed above.

Calculation of Topographic Disparity (TD)

By identifying a steep and flat power in each half of the cornea, a line can be drawn to delineate a superior and inferior semi-meridian. **Figure 10a** shows the steep meridians of the superior (45.16 / 47.37 at 160) and inferior (45.99/ 49.57 at 300) semi-meridians, measured by topography in the 5mm zone using keratometric display, as they would appear on the eye (360° polar diagram). The 5mm zone in this case has been chosen as this mid-zone region best represents the overall shape of the eye. The meridia are then doubled on a mathematical construct (**Figure 10b** DAVD) to enable vectorial calculation of the difference between the superior and inferior topography (i.e. the topographic disparity, TD). The superior topography (at 160O) is displayed at 320 degrees and the inferior topography (at 300O) to 600 degrees on a 720 degree DAVD. Note, however, that the topography magnitudes remain unchanged. Using trigonometric principles the TD is calculated and the orientation is, by convention, in the direction of superior to inferior topography. Placing this vector at the x=0, y=0 origin the axis is calculated as 206 degrees. The axis of the TD is then halved (103 degrees) to display its orientation on a 360O polar diagram as it would appear on the eye (**Figure 10c**).

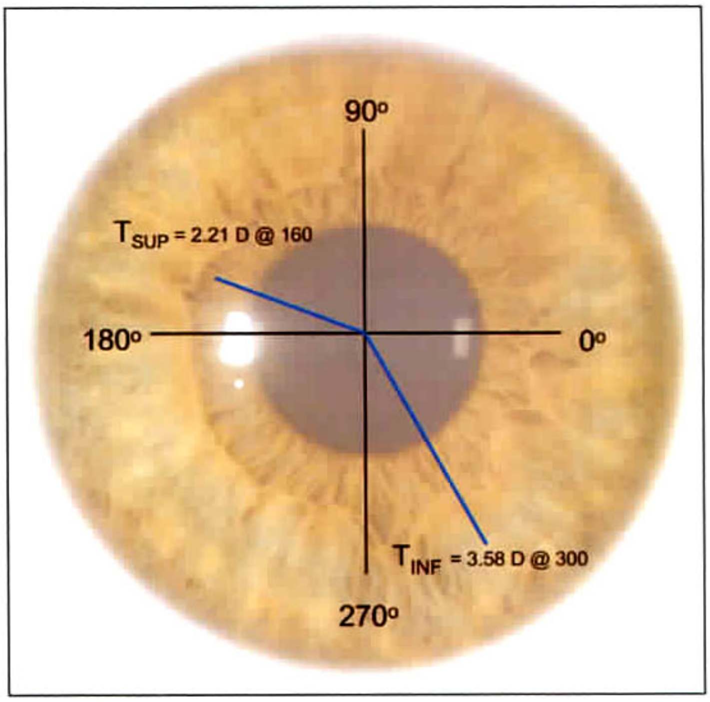


Figure 10A: (Polar diagram) Superior and inferior topography (simulated keratometry) in corresponding corneal semi-meridian.

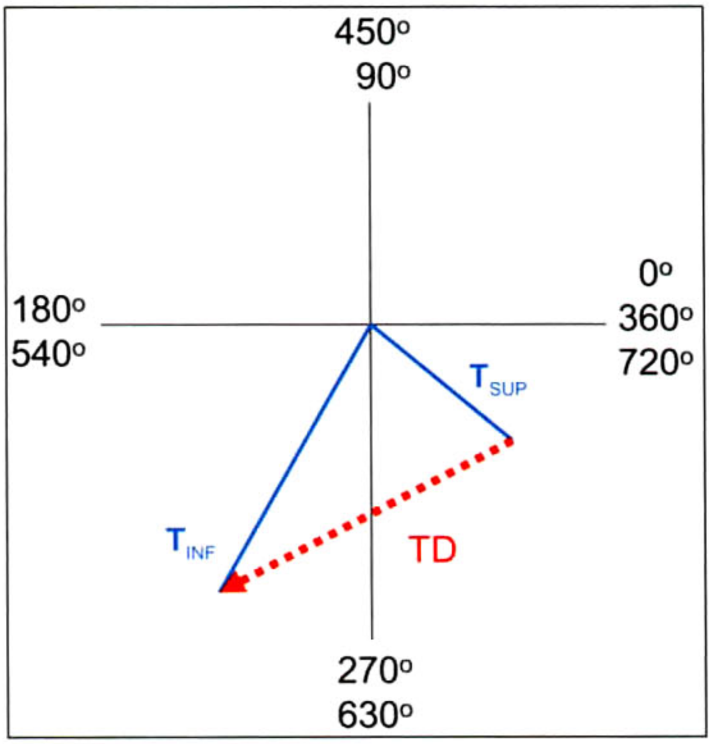


Figure 10B: (DAVD) Topographic meridia doubled but magnitudes unchanged – T_{SUP} is displayed at 320° and the T_{INF} at 600°. The vectorial difference equals the topographic disparity (TD).

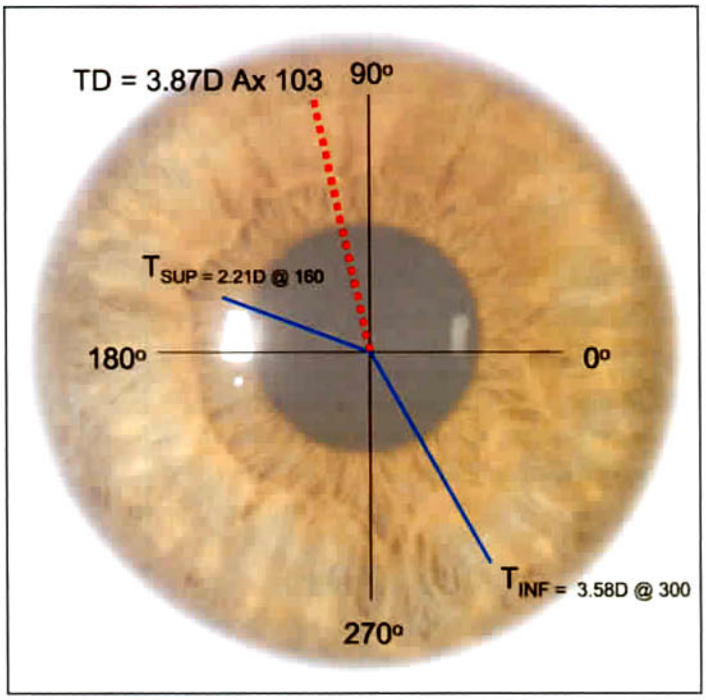


Figure 10C: (Polar diagram) TD as it would appear on the eye.

Asymmetrical Treatments Between the Two Semi-Meridians of the Cornea

It is the target induced astigmatism vector (TIA) that allows us to determine the astigmatic target of the surgery being performed and provide the means to achieve any amount or orientation of corneal astigmatism, as well as an objective and integrated astigmatic analysis of the outcome. When there are two distinct preoperative topography values on each semi-meridian, there will be differing calculated target values of refractive and topographical astigmatism after asymmetrical treatment. The different orientations of these upper and lower targets, which are determined by the preoperative combination of corneal and refractive parameters, enable the surgeon to decide on the relative emphases placed on eliminating corneal or refractive astigmatism in the separate treatment plan for the two semi-meridians.

Applying Vector Planning to Each Semi-Meridian

The diagram in **Figure 11** shows the polar astigmatism and surgical vector parameters as they would appear schematically on an eye. The semi-meridian is drawn at 180 degrees to display a flat and steep meridian superiorly and inferiorly, and the mathematical construct of a DAVD allows for the vectorial calculations of astigmatism treatments and targets. The astigmatism in both the superior and inferior semi-meridians is optimally treated by calculating the ORA and apportioning this to both the cornea and refraction postoperatively. It is important to understand that no matter what emphasis is chosen (0% to 100% refraction) the treatment of astigmatism is maximised. That is, the minimum amount of unavoidable astigmatism (the ORA) remains at both semi-meridians.

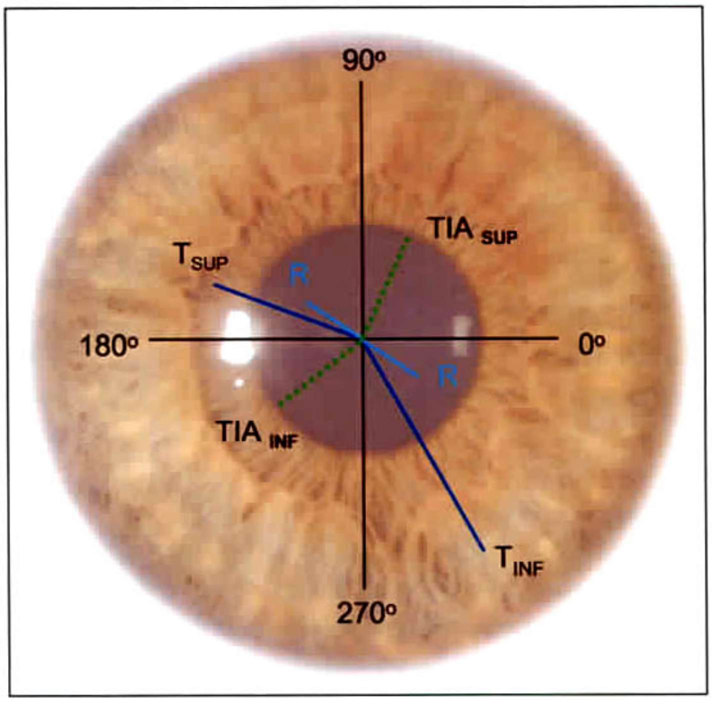


Figure 11: (Polar diagram) Treatment of irregular astigmatism by applying the asymmetric treatment to each corneal semi-meridian.

Separate treatment plans are required to optimally reduce and regularise the superior and inferior corneal astigmatism. This involves combining the topographic magnitude and meridian value of each semi-meridian with the common refractive astigmatism magnitude and axis value of the manifest refraction. The target astigmatism for each semi-meridian can then be calculated and the two TIA's (superior and inferior) determined **(Figure 11)**. When the TIA between the two semi-meridians differs, a summation of the TIA's (TIA_{NET}) or average, needs to be calculated to determine the combined effect on refractive astigmatism. This TIA_{NET} is then applied to the common refractive astigmatism value to determine the expected average refractive astigmatism value for the whole eye.

In practice, the superior and inferior semi-meridians of the cornea will always share a common refractive value when measured by manifest refraction. Consequently, the two calculated target refractive astigmatism targets (superior and inferior) are not separately perceived by the eye, and a single averaged target refractive value can be used to calculate the targeted outcome of asymmetrical corneal (superior and inferior) treatments, and consequently intraocular aberrations.

Future technology may enable measurement of separate refractive errors for each semi-meridian of the cornea by devices such as aberrometers. This would potentially improve visual outcomes further by an accurate measurement of pre and post operative readings. Further to this, regularisation of the topographic targets can be achieved after this *maximum reduction of the astigmatism*, by targeting the common refraction and hence reducing the ORA. Multiple variations to this maximum reduction and regularisation of astigmatism are possible, giving the surgeon the means to change the corneal shape to that desired. These include achieving orthogonal symmetrical astigmatism without changing the refractive astigmatism – hence the TIA_{NET} is 0.00D **(Figure 12)**. This offers the potential to improve uncorrected

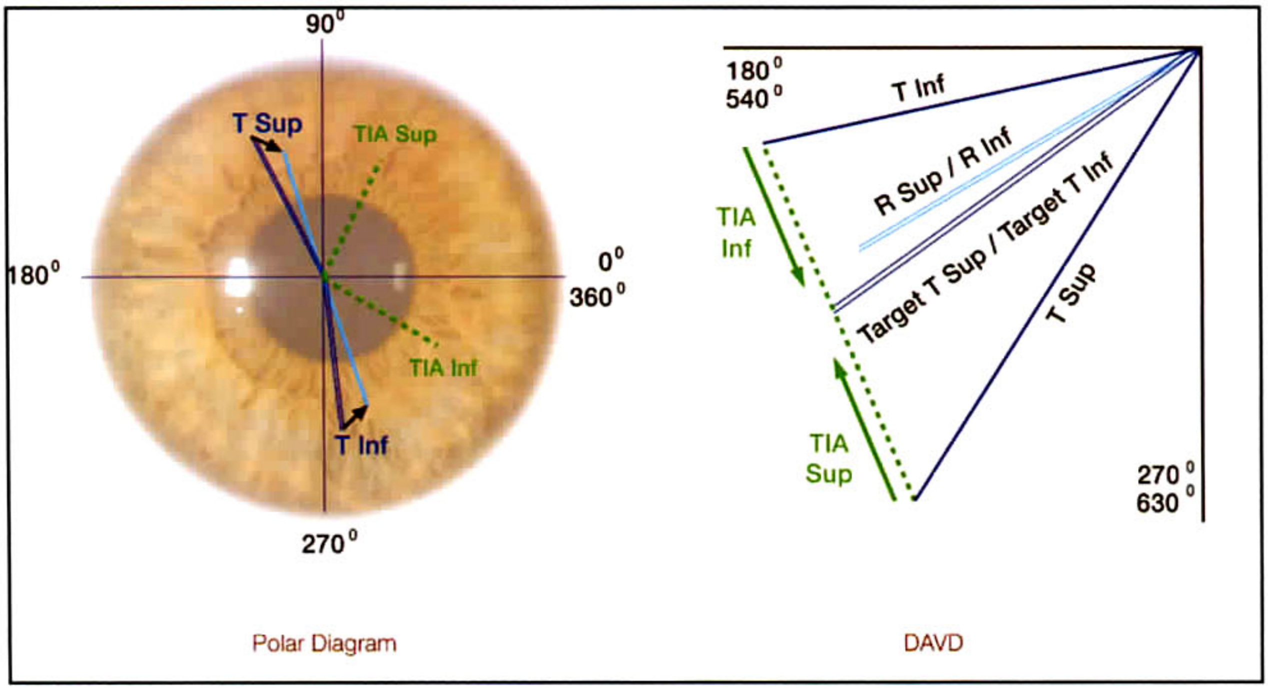


Figure 12: Polar and double angle vector diagram displaying the TIA as calculated separately for each semi-meridian without changing the refractive astigmatism.

or best corrected visual acuity. This approach provides treatment parameters that would result in no change in spherical equivalent or overall refractive status to the eye. A patient undergoing this treatment would not change their spectacles but be expected to have an improvement in the quality and quantity of vision, effectively improving the visual performance of any such eye with corneal irregularity.

Using the data and technology available to me I have sought to enable improved analysis of refractive surgery, an effort which has resulted in the concepts outlined above. However, the concepts I developed required software to analyze the myriad possibilities presented by this new set of principles. It was in 1992 that I first developed an outcomes analysis software program specifically designed for ophthalmology. I wanted the ability to review and analyze my data within minutes and to calculate appropriate astigmatic treatment paradigms. This software significantly helped me develop my ideas and was helped along by a fortunate encounter with a mining engineer who also happened to be a computer programmer. It turned out this mining engineer/computer programmer was very interested in my work, and how it relates to his explanation of mining; for example, starting at both sides of a mountain and digging a tunnel through to meet precisely in the middle. These phenomena prompted me to think about my analysis in a different way than I would have left to my own devices. This software continues to be a very valuable tool that I use daily for both planning and analyzing refractive laser and cataract surgery and is known as the ASSORT program (Alpins Statistical System for Ophthalmic Refractive surgery Techniques).

Patients will continue to raise the bar and demand a better quality of vision after their refractive surgery whatever its mode. Advanced planning for better control and reduction of astigmatism during surgical procedure, and ongoing analyses postoperatively will ultimately provide a higher level of patient satisfaction. We must remember that patients will forever have high expectations, and we must attempt as best we can to provide them with, at least significantly better vision approaching these expectations when perfection, although desired by patient and surgeon, may not be achievable.

Accordingly, we are obliged to assiduously advance our scientific processes and methods of analysis. It is not sufficient to rely only on simple analysis methods which deliver insufficient information, and continue unrelenting with what we have done in the past. As surgeons and scientists, we must approach innovation in a systematic and diligent way and open up our minds to the possibilities.

The question that comes to mind is why would we not want to cultivate our knowledge and understanding of astigmatism when a new method comes to light that not only achieves better results and their quantification for patients, but provides the ophthalmic surgeon with a methodology that will allow them to develop a better understanding of what they do and what they can ultimately offer. With my method I have attempted to add value to the refractive surgical field of ophthalmology, and have determined The Alpins Method to be a valuable mode in better satisfying patients.

I anticipate that in time my efforts will be adopted by more than the handful of surgeons currently employing my technique.

I do not pretend my method is the simple one that is commonly sought. Nor is it the preferable so called "easy button", but in truth, it's not implausibly complex either. It is simply a different, unambiguous and systematic process of analysis and procedure that will ultimately give patients the opportunity for better vision with reduced astigmatism remaining on the cornea. It is my hope that within the next decade the technology discussed in this chapter will be more widely known, and used by corneal refractive surgeons worldwide who have taken on the intellectual challenge of mastering this technique to better address corneal priorities.

Not everyone is convinced. The evidence justifies my conclusions, but I think most would agree it has merit. The journey of discovery, description and dissemination has been a long one, yet the case remains open, and the implications of my method working, if only to limited success, will not only improve practice and analysis, but will create a much happier population of resolved astigmatism sufferers. As a final point, I offer the reader this. Is it not true that by unlocking your mind to new ways of thinking you can only ever gain, and never lose? This is how I developed **The Alpins Method** in the first place, and this is how I endeavour to improve upon it. My overall desire and philosophy has always been, and will continue to be, the improvement of astigmatic treatment in cataract and refractive surgery.

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