Twelve

Chapter

ABERROMETRY AND TOPOGRAPHY IN THE VECTOR ANALYSIS OF REFRACTIVE LASER SURGERY

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INTRODUCTION

Refractive laser surgery techniques such as laser *in situ* keratomileusis (LASIK) and photorefractive keratectomy (PRK) are effective methods of treating spherical myopic errors up to 12D and hyperopic errors up to 6D, with good visual outcomes. However, generally more than half of the people who are suitable candidates for refractive surgery have enough astigmatism to warrant its inclusion in the surgical correction. As astigmatism has both direction and magnitude, its incorporation into the treatment makes planning more complex. It has been shown that vector analysis can improve the visual outcome of spherocylindrical treatments by combining the topographic and refractive astigmatic components to target a reduced level of corneal astigmatism compared to using refractive parameters alone.[1-9]

MEASUREMENT OF ASTIGMATISM

There are three differing categories of astigmatism; naturally occurring regular astigmatism, naturally occurring irregular astigmatism and secondary irregular astigmatism associated with ocular trauma, disease, infection or previous ocular surgery.[1] There are many different ways to measure astigmatism, some assessing corneal astigmatism only, and the others measuring refractive astigmatism including the internal optics of the eye. It is important in routine clinical practice to utilize more than one method in the pre-operative examination.

The manifest subjective refraction is a measure of the spherocylindrical correction required for the patient's perception of their best vision. The principal contribution to the cylindrical error is the corneal astigmatism, but also includes astigmatism from the internal optics of the eye (such as the crystalline lens) as well as the interpretation of the image by the cerebral cortex. The measured result depends on many variables such as chart illumination and contrast, test distance and room lighting.

The technology of wavefront analysis provides a spatially oriented refractive map of the pathway of light through the eye, which provides a greater amount of information on the refractive system than the manifest refraction data alone. It too includes the internal optics of the eye, but unlike subjective responses does not include the conscious perception of the cerebral cortex, thus giving no information regarding the nonoptical interpretation of astigmatic images on the retina and visual cortex. This subjective value conventionally forms part of the ablative treatment and is an important component for patient satisfaction. The application of wavefront analysis in the treatment plan is discussed further on.

Keratometry is a useful objective test to measure average corneal curvature at the paracentral region of the cornea. However, as it requires the manual alignment of optical mires to identify the steepest and flattest corneal axes, there is a potential problem with reproducing reliable results due to variability between different observers. Corneal topography, or computer assisted videokeratography (CAVK), provides a more detailed quantified view of the corneal astigmatism displayed as a map based on the measurement of refractive power of thousands of separate points over the entire cornea. Average topographical astigmatism can be represented by a simulated keratometry value, which is a mean value derived from a number of constant reference points. It is a best fit compromise, and determined in various ways by the different types of topographers.

SURGICAL PLANNING ~ REFRACTION, TOPOGRAPHY, OR BOTH?

In an ideal world the goal of astigmatic refractive surgery is to completely eliminate astigmatism from the eye and its optical correction. However, it has since been recognized that this is not possible in the majority of cases due to the inherent differences between corneal astigmatism (represented by the simulated keratometry value from topography) and refractive astigmatism (represented by lower [second] order aberrations from aberrometry).[6,7] Most surgeons traditionally treat the refractive value alone based on the principle that treating what the patient perceives to give their best corrected vision will provide a superior visual outcome.

However, this is not necessarily the case. Disregarding the shape of the cornea while changing it flies in the face of the fundamental principles of corneal surgery. In fact, simple arithmetic analysis shows that an excessive amount of corneal astigmatism may be left if treatment is applied exclusively based on the parameters derived from the refractive cylinder magnitude and axis.[2,5] This occurs because failing to align the maximum ablation closer to the flattest corneal meridia results in off-axis loss of effect when reducing corneal astigmatism. Consequently, lower (second) order astigmatic aberrations and (third order) coma would not be minimized, with more remaining than otherwise necessary.[1] This may result in post-surgical symptoms such as reduced visual acuity and contrast sensitivity, creating difficulty with night driving and thus actually diminishing satisfaction in a proportion of patients.

It becomes particularly important to consider this in patients with form fruste or mild keratoconus as there is usually a large discrepancy between the refractive and corneal astigmatism in these cases. It has been shown that optimizing the PRK treatment by combining the refractive parameters with the corneal topography can improve the total astigmatic and visual outcomes for these patients.[3]

As it becomes more widely recognized that a zero overall astigmatism is mostly unattainable, effective contemporary treatment methods target astigmatism outcomes that combine both the refractive and topographic measurements in the analytical planning process. This should ensure the distribution of the remaining astigmatism to achieve the optimal outcome. That is, choosing a maximal treatment that leaves the minimum amount of astigmatism in the most favorable orientation. With-the-rule astigmatism is more prevalent in the younger population undergoing laser vision correction, and is thought to be more visually tolerable to refractive perception than against-the-rule astigmatism (Javals rule).[5,7,10]

VECTOR ANALYSIS BY THE ALPINS METHOD

The surgical planning and analysis process is expedited by the implementation of computer and software technology. Calculations performed for the publication of this chapter utilized the ASSORT® program developed by the first author (the Alpins Statistical System for Ophthalmic Refractive surgery Techniques). It employs the principles of vector planning and analysis[1-8] and utilizes a paradigm that favors with-the-rule astigmatism while minimizing measurable postoperative refractive astigmatism quantified as second order aberrations.

The amount and axis of astigmatic change that the surgeon *intends* to induce is called the target induced astigmatism vector (TIA). This is determined by using an optimal combination of refractive and topographic data, as seen in the example later on. The surgically induced astigmatism vector (SIA) is the astigmatic change *actually* induced by the surgery. It is possible to determine whether the treatment was on-axis or off-axis, and also whether too much or too little treatment was applied by examining the various relationships between the SIA and TIA. The Correction index (CI) is the ratio of the SIA to TIA and ideally is 1.0. An overcorrection occurs if the CI is greater than 1.0 and less than 1.0 for an undercorrection. The magnitude of error (ME) is the arithmetic difference between the magnitudes of the SIA and TIA. This is positive for overcorrections and negative for undercorrections. The angle of error (AE) is the angle contained by the SIA and TIA vectors. If the achieved correction is oriented counterclockwise (CCW) to where it was intended then the AE is positive. If the achieved correction is clockwise (CW) to the intended axis then the AE is negative.

An absolute measure of success of the surgery is described by the difference vector (DV). This is the induced astigmatic change that would enable the initial surgery to achieve its intended target, and is ideally zero. The DV is a useful dioptric measure of uncorrected astigmatism. A relative measure of success is the Index of success (IOS) which is calculated by dividing the DV by the intended change, the TIA. This is also preferably zero.

As previously mentioned, the corneal and refractive astigmatism are rarely equivalent. This difference may be represented vectorially by the ocular residual astigmatism (ORA).[11] In other words, the ORA is the noncorneal component of total refractive astigmatism, and quantifies by magnitude and axis orientation the minimum intraocular second order astigmatism aberrations. It is also the amount of corneal astigmatism expected to remain after treatment guided by refractive values alone, to neutralize this intraocular astigmatism.

ABERROMETRY AND WAVEFRONT GUIDED TREATMENT

Wavefront technology offers theoretical guidance to reduce spherical aberrations by achieving the most effective prolate aspheric profile. However, wavefront-assisted LASIK does not address the amount of resultant corneal astigmatism, and therefore is similar to LASIK based on manifest refraction. In addition, as aberrometry includes the internal optics of the eye in its calculations, any changes over time to the crystalline lens may undermine any benefit gained from the wavefront ablation.[1,9]

Furthermore, if wavefront guided ablation corrects all ocular aberrations at the corneal surface, it would produce an uneven corneal treatment resulting in induced corneal irregularities. This might be an undesirable result when it is widely recognized that a regular cornea with orthogonal and symmetrical astigmatism gives a superior visual result.[1,8] Permanently changing regional corneal shape in this manner is also complicated by the fact that this form of treatment may in fact be neutralized by epithelial healing.[9] Despite these potential limitations wavefront technology does provide useful refractive information. Rather than employing wavefront data exclusively, it can be combined with the vector planning method described in this chapter to produce an optimal treatment with reduced post-surgical aberrations.

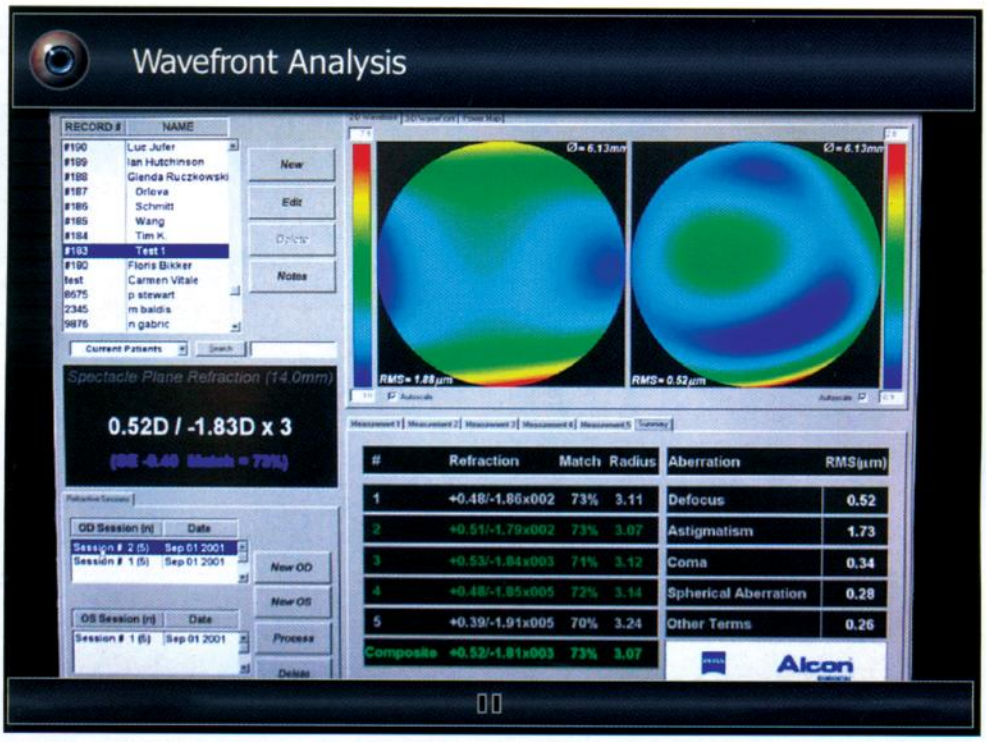
Combining Wavefront Analysis and Topography with Vector Planning

A typical wavefront analysis is depicted in Figure 12.1. The spherocylindrical refraction as measured by the wavefront device at the spectacle plane is +0.52/–1.83 × 3. The two dimensional illustration of the wavefront analysis on the left shows a moderate level of mixed astigmatism with a typical saddle appearance. The higher order spherical aberrations are quantified as root-mean-square values in the lower right hand corner of the display. The spherical component of the correction (+0.52) is shown as the defocus. The cylindrical component is displayed beneath this. Third order aberrations (coma and trefoil) are listed separately, with 4th order spherical aberrations. 'Other terms' indicates 5th order and higher order aberrations.

Figure 12.2 displays a topographical map of the matching astigmatic eye. The typical bow-tie appearance of the regular corneal astigmatism is evident. In this example the astigmatism measures 2.62 D at the steepest meridian of 96 degrees as quantified by the simulated keratometry values. These parameters can then be examined together with those from the wavefront analysis spherocylindrical (second order) values to produce an optimal treatment by using the Alpins method contained in the ASSORT® program. This is shown in the treatment planning screen in Figure 12.3. In this diagram the treatment has been set to a base of 100% emphasis for correction of refractive astigmatism parameters.

This treatment screen in Figure 12.3 has been disassembled further for ease of understanding the various components. Figure 12.4 is the top central section on the ASSORT® treatment screen, displaying the preoperative spherocylindrical refractive values taken from the wavefront analysis and also the corneal plane conversion. The cylindrical component here is 1.81D of astigmatism at axis 3. This figure also displays the spherocylindrical target for the treatment, which in this case is zero.

The treatment vector being employed is shown in the polar diagram in Figure 12.5. Here the TIA is 1.81D at axis 3. The pre and post-operative target astigmatism values are shown in Figure 12.6. The post-operative



RECORD #	NAME
#190	Luc Jufer
#189	Ian Hutchinson
#188	Glenda Ruczkowski
#187	Orlova
#186	Schmitt
#185	Wang
#184	Tim K.
#183	Test 1
#180	Floris Bikker
test	Carmen Vitale
8675	p stewart
2345	m baldis
9876	n gabric

Spectacle Plane Refraction (14.0mm)

0.52D / -1.83D x 3

(SE -0.40 Match = 73%)

RMS = 1.88 μm

RMS = 0.52 μm

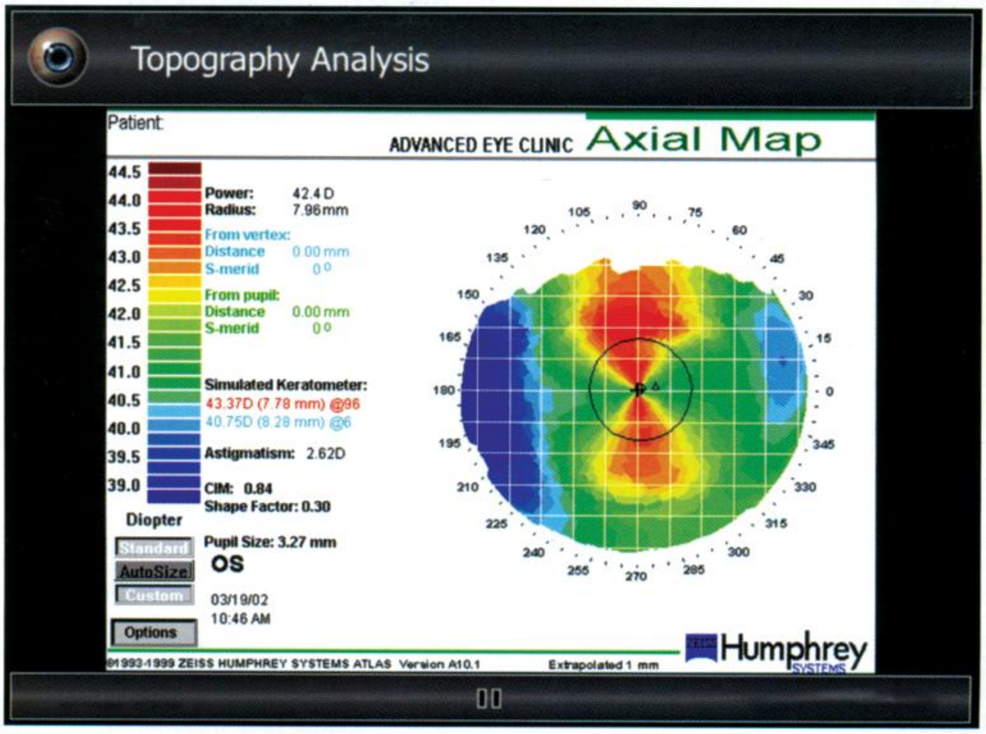
OD Session (n)	Date
Session # 2 (5)	Sep 01 2001
Session # 1 (5)	Sep 01 2001

OS Session (n)	Date
Session # 1 (5)	Sep 01 2001

#	Refraction	Match	Radius
1	+0.48/-1.86x002	73%	3.11
2	+0.51/-1.79x002	73%	3.07
3	+0.53/-1.84x003	71%	3.12
4	+0.48/-1.85x005	72%	3.14
5	+0.39/-1.91x005	70%	3.24
Composite	+0.52/-1.81x003	73%	3.07

Aberration	RMS(μm)
Defocus	0.52
Astigmatism	1.73
Coma	0.34
Spherical Aberration	0.28
Other Terms	0.26

Figure 12.1: A typical wavefront analysis display



Patient:

Power: 42.4 D
Radius: 7.96 mm
From vertex:
Distance 0.00 mm
S-merid 0°
From pupil:
Distance 0.00 mm
S-merid 0°

Simulated Keratometer:
43.37D (7.78 mm) @96
40.75D (8.28 mm) @6

Astigmatism: 2.62D

CIM: 0.84
Shape Factor: 0.30

Pupil Size: 3.27 mm
OS

03/19/02
10:46 AM

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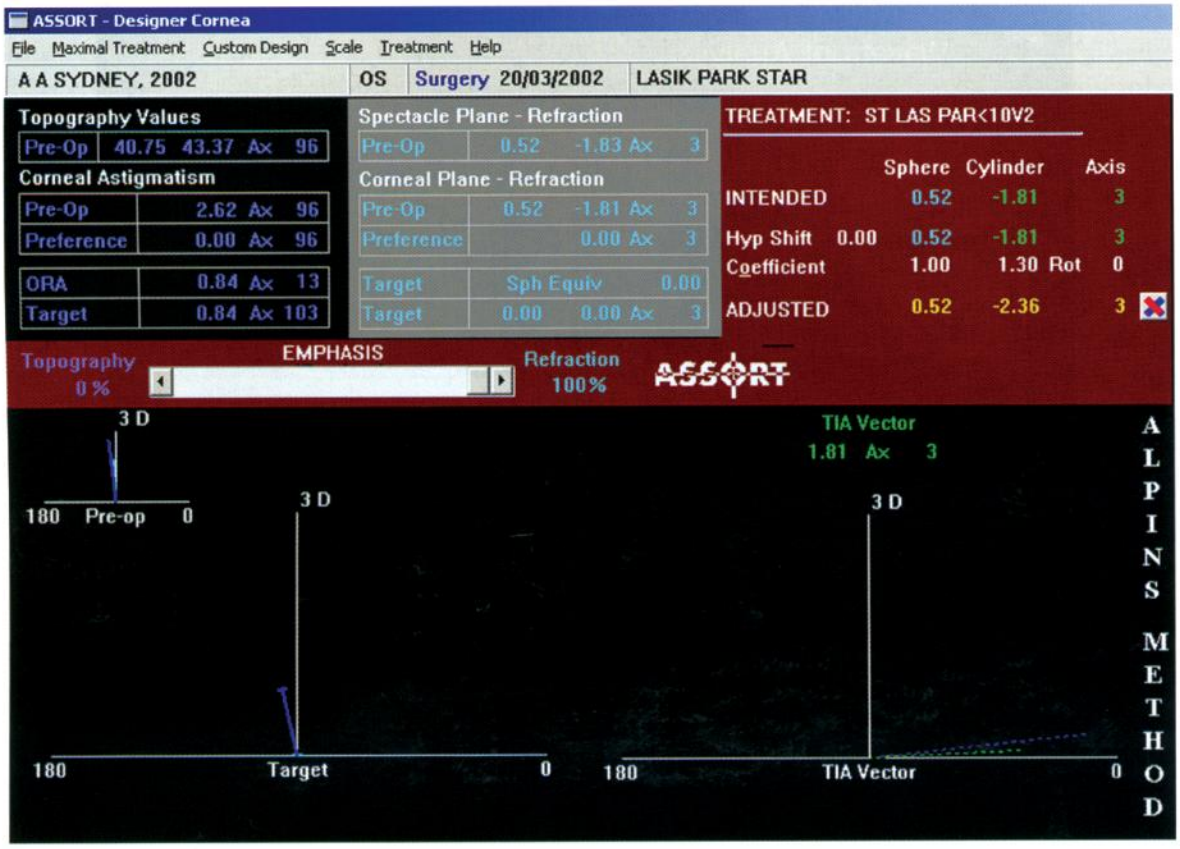
Extrapolated 1 mm

Figure 12.2: Topographical analysis of the same eye



A A SYDNEY, 2002 OS Surgery 20/03/2002 LASIK PARK STAR

Topography Values

Pre-Op	40.75	43.37	Ax	96

Corneal Astigmatism

Pre-Op	2.62	Ax	96
Preference	0.00	Ax	96
ORA	0.84	Ax	13
Target	0.84	Ax	103

Spectacle Plane - Refraction

Pre-Op	0.52	-1.83 Ax	3

Corneal Plane - Refraction

Pre-Op	0.52	-1.81 Ax	3
Preference		0.00 Ax	3
Target	Sph Equiv		0.00
Target	0.00	0.00 Ax	3

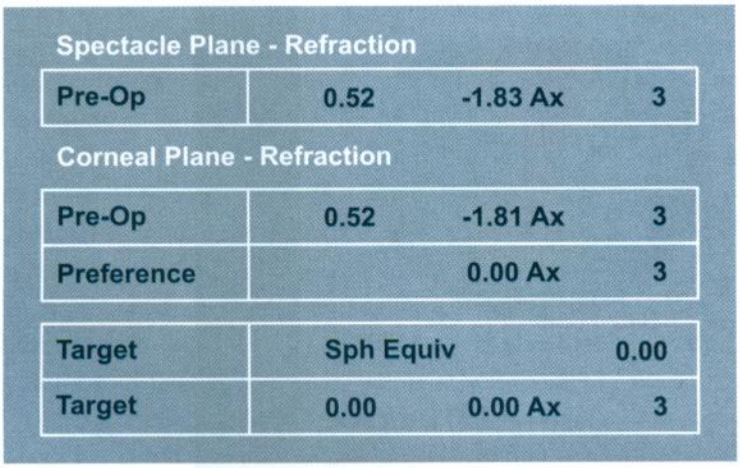
TREATMENT: ST LAS PAR<10V2

		Sphere	Cylinder	Axis
INTENDED		0.52	-1.81	3
Hyp Shift	0.00	0.52	-1.81	3
Coefficient		1.00	1.30 Rot	0
ADJUSTED		0.52	-2.36	3

Topography 0 % Refraction 100%

TIA Vector 1.81 Ax 3

Figure 12.3: The ASSORT surgical planning module for this eye



Spectacle Plane - Refraction

Pre-Op	0.52	-1.83 Ax	3

Corneal Plane - Refraction

Pre-Op	0.52	-1.81 Ax	3
Preference		0.00 Ax	3
Target	Sph Equiv		0.00
Target	0.00	0.00 Ax	3

Figure 12.4: The top central section of the ASSORT screen displaying the preoperative refractive data obtained from the wavefront analysis (both spectacle and corneal plane values) and the chosen refractive spherocylindrical target

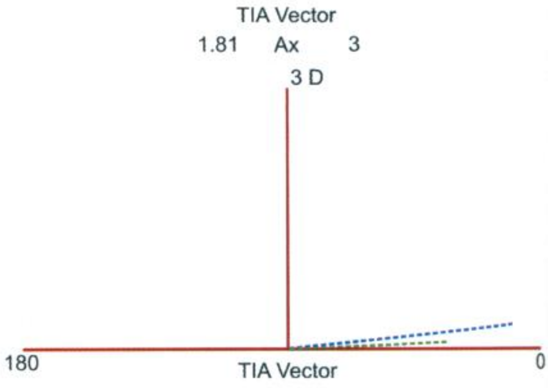


Figure 12.5: The lower right hand graph on the ASSORT screen with a polar display of the TIA vector

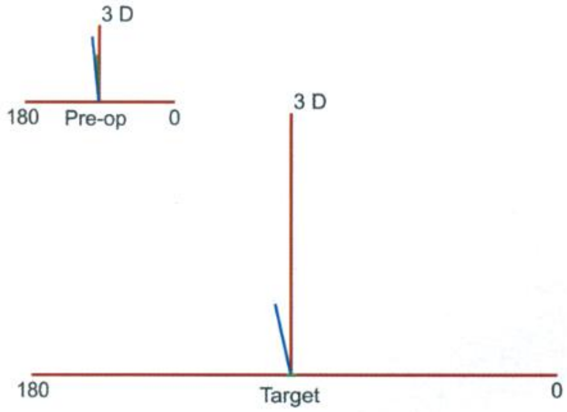
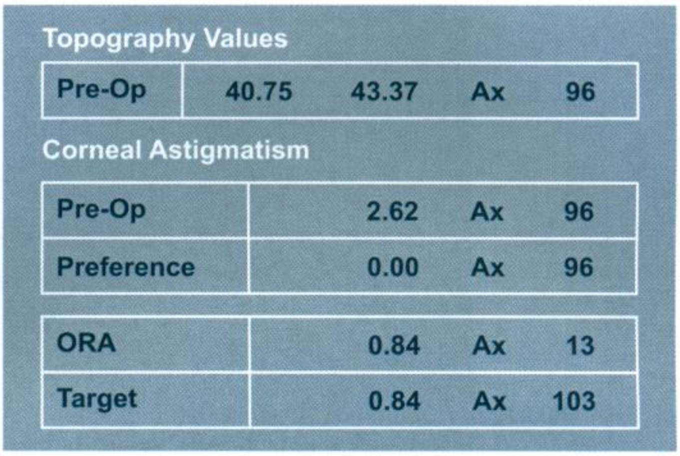


Figure 12.6: Preoperative and postoperative target astigmatism vectors. The postoperative refractive target value is zero with the target corneal astigmatism vector displayed in green



Topography Values

Pre-Op	40.75	43.37	Ax	96

Corneal Astigmatism

Pre-Op	2.62	Ax	96
Preference	0.00	Ax	96
ORA	0.84	Ax	13
Target	0.84	Ax	103

Figure 12.7: The top left hand box of the ASSORT screen displaying the corneal topographical preoperative values and the targeted corneal postoperative value. The minimum amount of astigmatism is displayed as the ORA, which in this case matches the magnitude target for the corneal astigmatism and is 90 degrees away

refractive target value is zero with the target corneal astigmatism value (obtained from Figure 12.7) displayed in blue.

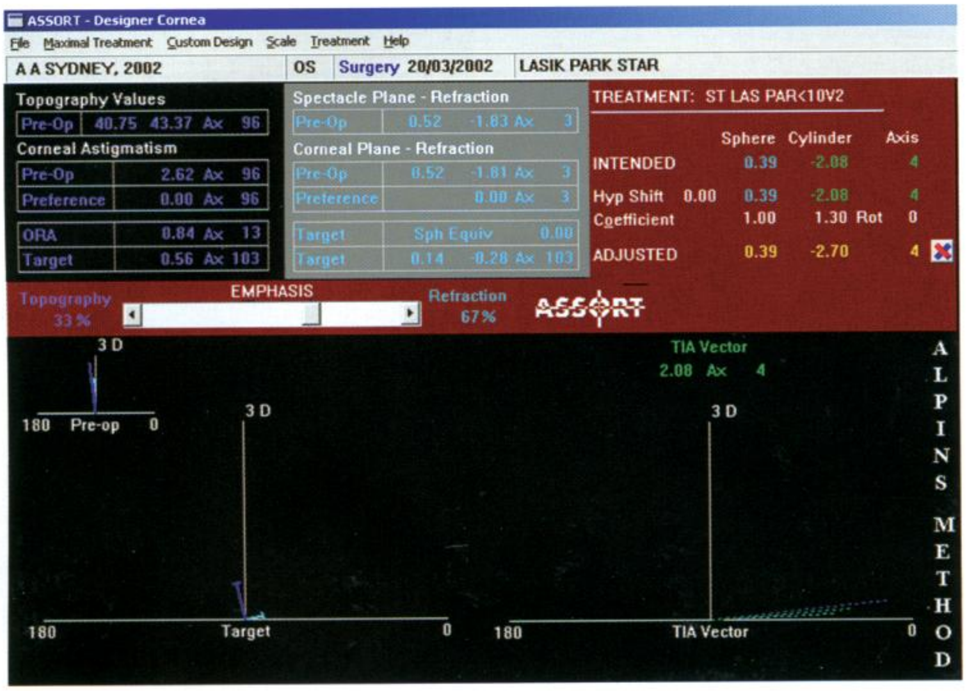
The simulated keratometry values from the preoperative topographical map are shown in Figure 12.7. Also displayed here are the ORA and the target for the corneal postoperative astigmatism. A vectorial calculation is used to determine the ORA, which in this case is 0.84 D. That is, there is a calculated amount of 0.84 D of intraocular astigmatism that cannot be eliminated from this eye. As the spherocylindrical refractive target has already been guided to zero, this can only leave the whole of the remaining astigmatism on the cornea at a near vertical meridian of 103 degrees to neutralize the ORA 90 degrees away, as seen in the target value of Figure 12.7.

However, as the emphasis is shifted towards the left, the treatment is more closely aligned to the principal corneal meridian. Figure 12.8 shows the optimal treatment for this eye, with the emphasis placed at 33% topography and 67% refraction. The ORA is still 0.84 D, but now it is apportioned between the refraction and the cornea. Here less corneal astigmatism is targeted and has been reduced to 0.56D at an unchanged meridian 103 (Figure 12.9). The remaining 0.28 D which is included in the spherocylindrical target of a spherical equivalent of zero, is not necessarily detected by the perceptive system at these levels, particularly as it is oriented favorably towards with-the-rule. Thus, with this method of vectorial planning, although the targeted sphero-cylindrical outcome is not zero, but 0.14/-0.28 ×103 as displayed in Figure 12.10, the measured postoperative refractive and wavefront astigmatism is likely to be negligible.

Despite not targeting a zero sphero-cylindrical outcome, by directing the remaining astigmatism away from the cornea the overall astigmatism is also less, and there are fewer aberrations remaining. This treatment results in an overall higher patient satisfaction.

TREATMENT OF IRREGULAR ASTIGMATISM

Differences in the two opposite superior and inferior hemidivisions of the corneal topographical contour map are widely prevalent. This is known as irregular astigmatism and occurs if the two sides of the bow-tie representation differ in magnitude (asymmetrical) or are not aligned at 180 degrees to each other (nonorthogonal), or most commonly a combination of the two.[1,8] Irregular astigmatism may also be identified



A A SYDNEY, 2002 | OS | Surgery 20/03/2002 | LASIK PARK STAR

Topography Values

Pre-Op	40.75	43.37	Ax	96

Corneal Astigmatism

Pre-Op	2.62	Ax	96
Preference	0.00	Ax	96
ORA	0.84	Ax	13
Target	0.56	Ax	103

Spectacle Plane - Refraction

Pre-Op	0.52	-1.83	Ax	3

Corneal Plane - Refraction

Pre-Op	0.52	-1.81	Ax	3
Preference		0.00	Ax	3
Target	Sph Equiv			0.00
Target	0.14	-0.28	Ax	103

TREATMENT: ST LAS PAR<10V2

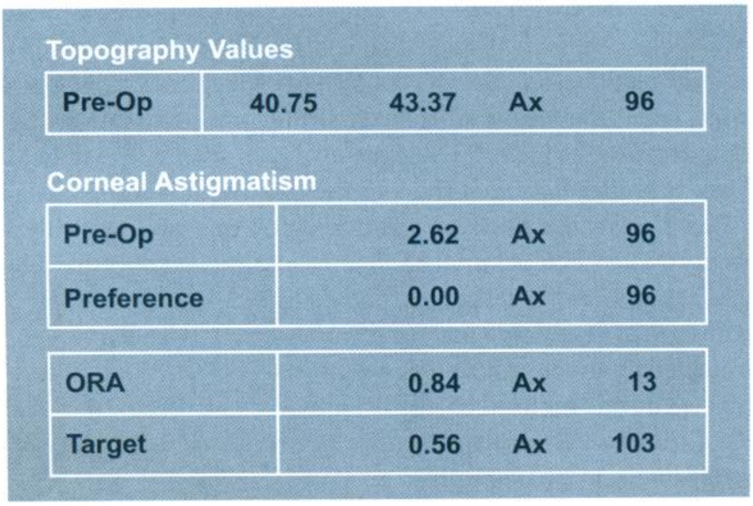
		Sphere	Cylinder		Axis
INTENDED		0.39	-2.08		4
Hyp Shift	0.00	0.39	-2.08		4
Coefficient		1.00	1.30	Rot	0
ADJUSTED		0.39	-2.70		4

Topography 33 %

Refraction 67 %

TIA Vector 2.08 Ax 4

Figure 12.8: The ASSORT treatment screen displaying the optimal treatment for the same eye. Here the emphasis bar has been shifted 33% towards the left so that not all of the surgical emphasis is placed on complete refractive astigmatism correction



Topography Values

Pre-Op	40.75	43.37	Ax	96

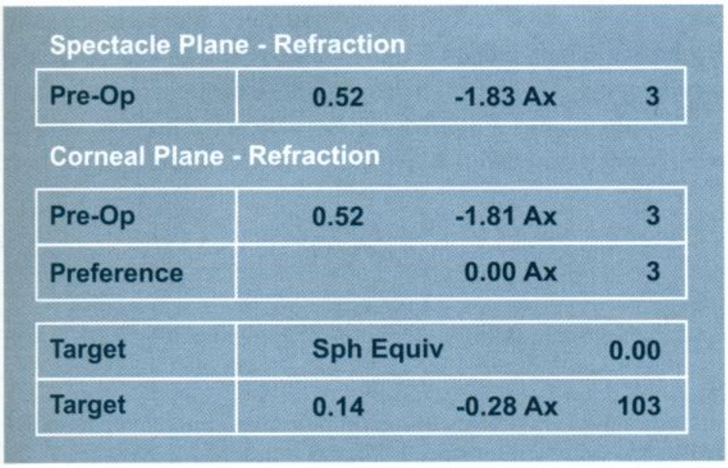
Corneal Astigmatism

Pre-Op	2.62	Ax	96
Preference	0.00	Ax	96
ORA	0.84	Ax	13
Target	0.56	Ax	103

Figure 12.9: The optimal treatment for the same eye. Here the amount of corneal astigmatism remaining after treatment has been reduced by one third to 0.56D, though the total ORA remains unchanged at 0.84D

optically using wavefront devices. Unlike other methods of astigmatism analysis, the method described in this chapter may theoretically also be applied independently to each hemidivision in a cornea displaying pre-existing idiopathic irregularity. This would theoretically allow analysis and treatment of this irregular astigmatism to produce an orthogonal, symmetrical cornea.

The target refractive and corneal astigmatism values must be considered separately for each hemimeridian, with individual treatment plans required for both the superior and inferior topographic magnitudes and



Spectacle Plane - Refraction

Pre-Op	0.52	-1.83 Ax	3

Corneal Plane - Refraction

Pre-Op	0.52	-1.81 Ax	3
Preference		0.00 Ax	3
Target	Sph Equiv		0.00
Target	0.14	-0.28 Ax	103

Figure 12.10: The new spherocylindrical target for this eye is not zero, but 0.14/-0.28x103. This distributes the ORA between the post-operative refractive and corneal modes to produce a more favorable corneal shape and therefore less second order aberrations following surgery. The favorably oriented and minimal refractive target is not likely to be perceived by the patient

meridian values with the common refractive astigmatism value. From this, minimum target astigmatism values may be calculated for each part of the cornea, and their orientations are used to guide the choice for the optimal TIA for that side.[8]

The vectorial difference between the two opposite semimeridian values for magnitude and axis in each corneal part is called the topographic disparity (TD). When displayed on a 720 degree double-angle vector diagram, the TD quantifies the irregular astigmatism of the cornea in diopters, and the treatment required to reduce or eliminate the irregular astigmatism can be determined from this.[8]

The information gained from computerized topography regarding the corneal height (either directly such as the Z dimension on the Orbscan device, or indirectly inferred from slope measurement) may be translated into planned tissue ablation patterns using the Munnerlyn formula. This ablative pattern may then be applied at specific points on the corneal surface to reduce the irregularity.[1] There are various methods to link topographical information with tailored ablation, though a real time preoperative link is yet to be achieved.

In this way, the corneal shape may be manipulated by asymmetrical surgical treatment to the irregular hemidivisions of the cornea, allowing the achievement of any corneal shape (thus producing regular astigmatism where selected). In cases of irregular astigmatism a rearrangement rather than a reduction of the corneal astigmatism may be of benefit, as regularizing the cornea may improve best corrected visual acuity to better approach the goal of supernormal vision.

SUMMARY

Due to natural differences in the vast majority of eyes between total astigmatism as measured by refraction and corneal techniques, it is impossible to completely eliminate astigmatism from the eye's optical system and its correction. It can therefore be beneficial to combine both these elements when considering the plan for refractive laser surgery to produce an optimal, individualized outcome. If the treatment plan utilizes manifest refraction data alone, it may actually increase the postoperative aberrations, thereby reducing the final visual result.

The Alpins method of vector planning utilizes information from both corneal topography and manifest refraction/wavefront data to target less postoperative corneal astigmatism and minimize postoperative aberrations. Though this often means that the postoperative refractive astigmatism target is not zero, this minor refractive error (with a spherical equivalent of zero) that remains postoperatively in a favorable orientation may not be significant enough for patient perception. In fact, overall the patient satisfaction is potentially higher due to the lesser amount of lower order aberrations.

This method of vector planning and analysis may also be used to optimize treatment for each separat hemimeridian of the cornea in cases of irregular astigmatism. This would enable the surgeon to rearrange th corneal astigmatism and regularize the cornea, thus producing a potential increase in the best corrected visua acuity. Though a real time preoperative link to the topographical and wavefront information for this specialize ablation is yet to be formed, this integration of these diagnostic modalities utilizing vector planning may be reality in the future.

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* of special interest