CHAPTER 19

Treating Stable Corneas

Combined Consideration of Wavefront- and Topography-Guided Treatment

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The term *customized* software has been used in refractive laser surgery to describe wavefront-guided or topography-guided treatments. A number of papers[1-4] have presented another level in this concept of "customization" where treatments incorporate a combination of refractive (wavefront or manifest) and corneal parameters (topography or keratometry). The Alpins method[1,2,5] is a technique of vector planning combining refractive and corneal parameters to treat regular and irregular astigmatism.

Treatment of astigmatism conventionally involves consideration of the wavefront or manifest refraction alone. In some cases[6,7] of irregular astigmatism, such as those presented in Figure 19-1, topography-guided ablations have been given preference with limited astigmatic outcomes. Despite a large amount of information provided by current aberrometry and topography systems about the optical system of the eye and the corneal shape, each of these devices used for treating astigmatism has its limitations.

Limitations

Wavefront-guided ablations do not address the neutralization of the intraocular (noncorneal) astigmatism that remains on the cornea postoperatively. If treatment were performed using refractive parameters alone, an excessive and unnecessary amount of corneal astigmatism would be left. "Sculpting" one refractive astigmatism onto a corneal astigmatism of different magnitude and/or axis can result in a third cylinder of astigmatism with greater magnitude than the original preoperative astigmatism.[5,9] Consequently, lower second-order astigmatic aberrations and third-order coma and trefoil would not be minimized by treatment. This would potentially compromise visual acuity and contrast sensitivity outcomes, particularly under mesopic conditions. Unfortunately with this approach, topographic values are not taken into account.

With wavefront-guided ablation, there is no consideration of the patient's subjective appreciation of astigmatism, which is related to the visual cortex of the brain. The cortical perception may 'accept' some, or all, of the astigmatism, resulting from the wavefront refraction and, as a result, the patient does not perceive any visual problem. This acceptance of the wavefront refraction by the visual cortex is best reflected in the manifest refraction and hence the need to cross-check the manifest with the wavefront refraction to ensure that the spherical and astigmatic components of each are comparable. The inclusion in the treatment of a patient's conscious perception of their refractive astigmatism is likely to benefit their satisfaction.[10,11]

If practitioners attempt to correct all ocular aberrations measured by aberrometry at the corneal surface, it would result in corneal surface irregularities.[10] In order to obtain the best possible astigmatic outcome, it would be advantageous to have a regular cornea with orthogonal and symmetrical orientation.[1] It is important to note that even eyes with normal (emmetropic) vision can suffer from aberrations that affect functional vision.[12]

Topography-guided treatments alone do not consider the fact that the amount of astigmatism at the corneal plane often differs from the refractive (second-order) astigmatism. As a result, treatments based entirely on the map generated from a topographer or aberrometer may not achieve the full potential of optimum outcomes.

The treatment of astigmatism would be straightforward if refractive and corneal astigmatism always coin-

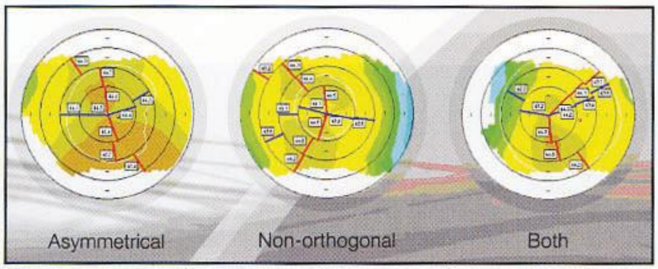


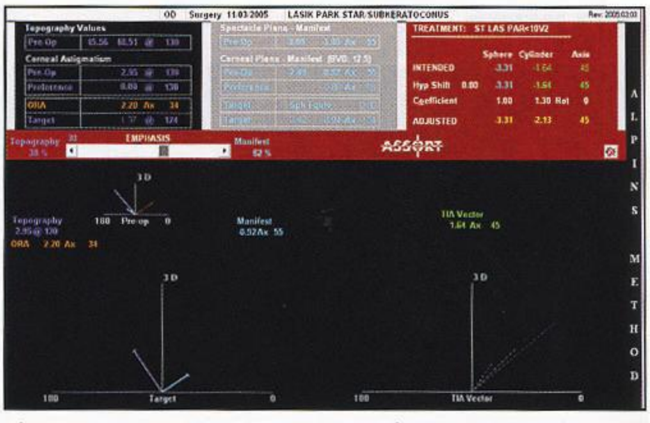
Figure 19-1. Displays the various topography patterns of naturally occurring irregular astigmatism.

cided in magnitude and axis. Variance between manifest or wavefront refraction and keratometry or topography is widely prevalent, however, and the consequence is that an inevitable amount of astigmatism remains in the optical system of the eye after treatment. Eyes with irregular astigmatism have, in general, a poorer correlation between corneal and refractive values compared to the values for a normal astigmatic population.[13]

The difference in magnitude, orientation, or both is gauged by the ocular residual astigmatism (ORA)[1,2,5,9,10] and can be quantified by calculating, in diopters, the vectorial difference between refractive and corneal astigmatism. The ORA value is equivalent to the amount of neutralizing astigmatism that will remain on the cornea if only refractive astigmatism is corrected. The ORA has also been referred to as intraocular,[14] lenticular,[15] and noncorneal astigmatism.[16]

Calculation of Ocular Residual Astigmatism

Consider the example in Figure 19-2. The manifest refraction finds astigmatism of −0.92458 DC Ax 55 at the corneal plane. Thus, the power axis is at 145 degrees. The corneal astigmatism is 2.95 D at 130 shown by the simulated keratometry, a best-fit line, from the topography measurement. The manifest refraction cylinder (R) and the corneal astigmatism (SimK) are represented on a polar diagram in Figure 19-3A. The ORA is the vectorial difference between the measured corneal and refractive astigmatism. It can be calculated by doubling the angles of the refractive (290 degrees) and corneal (260 degrees) astigmatic axes as shown in Figure 19-3B on a double-angle vector diagram (DAVD) and leaving the magnitudes unchanged. Using trigonometric principles to determine the difference between the two, the ORA on the DAVD = 2.20 D Ax 68. This ORA vector is then taken to the origin (x = 0, y = 0) and halved to convert it back to a polar diagram (Figure 19-3C; ORA = 2.20 D Ax 34), which represents the parameters within the optical system of the eye.[1,2,6,17,18]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Topography Values
Pre Op 45.56 48.51 @ 130

Corneal Astigmatism
Pre-Op 2.95 @ 130
Preference 0.00 @ 130
ORA 2.20 Ax 34
Target 1.37 @ 124

Spectacle Plane - Manifest

Corneal Plane - Manifest (BVD: 12.5)

TREATMENT: ST LAS PAR<10V2

		Sphere	Cylinder	Axis
INTENDED		-3.31	-1.64	45
Hyp Shift	0.00	-3.31	-1.64	45
Coefficient		1.00	1.30 Rot	0
ADJUSTED		-3.31	-2.13	45

Topography 38 %
EMPHASIS
Manifest 62 %

Topography 2.95@ 130
ORA 2.20 Ax 34
Manifest 0.92Ax 55
TIA Vector 1.64 Ax 45

Figure 19-2. ASSORT Treatment Planning shows how the ORA of 2.20 D Ax 34 is apportioned 38% to eliminating the topography astigmatism and 62% to the refractive cylinder. Furthermore this ORA is neutralized by an equivalent 1.37 D at the cornea and −0.84 DC at the spectacle refraction but at an orientation of 124 degrees.

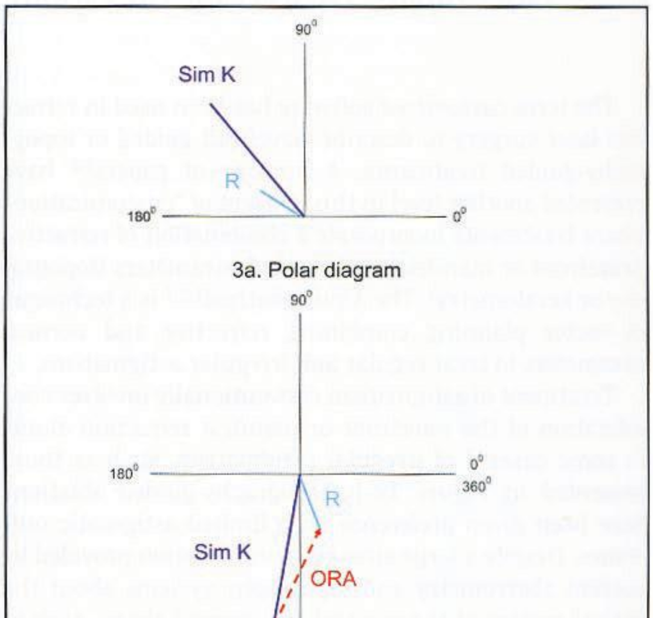
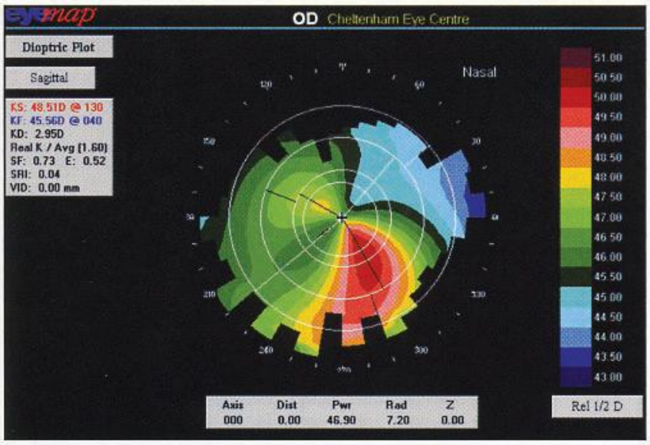


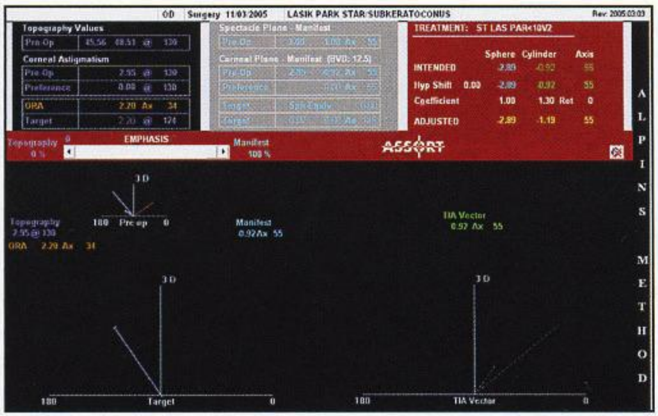
Figure 19-3. Calculation of ORA. (A) Polar diagram of refractive cylinder at positive axis and simulated keratometry. (B) DAVD showing a doubling of the angles without a change in the astigmatic magnitudes. (c) Polar diagram displaying the ORA as it would appear on the eye.



KS: 48.51D @ 130
KF: 45.56D @ 040
KD: 2.95D
Real K / Avg (1.60)
SF: 0.73 E: 0.52
SRI: 0.04
VID: 0.00 mm

Axis	Dist	Pwr	Rad	Z
000	0.00	46.90	7.20	0.00

Figure 19-4. Topography map displaying nonorthogonal, asymmetric bow-tie in irregular astigmatism.



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Topography Values

Pre-Op	45.56 48.51 @ 130

Corneal Astigmatism

Pre-Op	2.95 @ 130
Preference	0.00 @ 130
ORA	2.20 Ax 34
Target	2.20 @ 124

Spectacle Plane - Manifest

Corneal Plane - Manifest (BVD: 12.5)

TREATMENT: ST LAS PAR<10V2

	Sphere	Cylinder	Axis
INTENDED	2.89	-0.92	55
Hyp Shift 0.00	-2.89	-0.92	55
Coefficient	1.00	1.30 Ret	0
ADJUSTED	-2.89	-1.19	55

Topography 0 0 %

Manifest 100 %

Topography 2.95 @ 130

ORA 2.20 Ax 34

Manifest 0.92 Ax 55

TIA Vector 0.92 Ax 55

Figure 19-5. The ASSORT treatment screen displays both the manifest refraction and the corneal astigmatism by topography. The emphasis shown here is that of conventional treatment, 0% topography/100% manifest refraction.

By quantifying the vectorial difference between the corneal and the refractive astigmatism using the ORA, the maximum correction of astigmatism can be achieved. The distribution of the remaining ORA needs to be considered carefully. Do we leave this totally on the cornea by treating with manifest wavefront refraction, as is customary practice, or is it better to distribute the astigmatism between the two in a favorable optimized manner?

Certainly, it would be advantageous to be able to reduce a greater amount of corneal astigmatism by allocating some of the ORA to the refraction, directing the treatment closer to the principal corneal meridian thereby creating less "off-axis" effect.[9] In this way, the corneal shape changes more favorably with less astigmatism remaining. The treatment is less likely to create distortion of optics created by excess cross-cylinder effect induced by the change. The reduction in corneal astigmatism substantially exceeds the increase in measurable refractive cylinder. This has the overall effect of minimizing the total amount of refractive + topographic astigmatism remaining after laser surgery required to neutralize the ORA. This results in a better refractive outcome, a greater potential for improvement in best corrected visual acuity and reduced second-order aberrations, coma, and trefoil, principally by reducing the amount of remaining corneal astigmatism.[1,2,10]

Combining Wavefront and Topographic Data Using Vector Planning

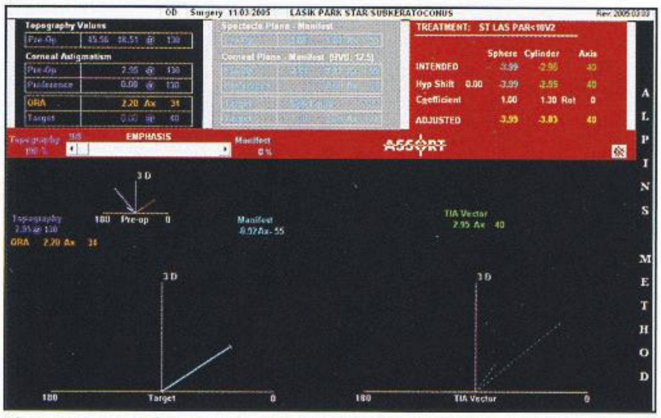
Using vector planning, refractive and corneal information can be combined. The advantages of addressing both corneal and refractive astigmatism preoperatively reduces the level of astigmatism that is left on the cornea compared to using refractive parameters alone and, as a result, fewer second- and third-order aberrations may remain.[1,2,10,17,18]

The calculations performed in this chapter utilize the ASSORT program (Alpins Statistical System for Ophthalmic Refractive surgery Techniques) developed at NewVision Clinics. The program uses vector planning and analysis in a paradigm that has the option to favor with-the-rule astigmatism. With this method corneal astigmatism is taken into account and reduction in postoperative refractive astigmatism is optimized.[1,2,5,10,18] The spherocylindrical refraction as measured by manifest refraction (see Figure 19-2) at the spectacle plane is −3.00 DS −1.00 DC Ax 55.

Figure 19-4 displays the topographic data of the same astigmatic eye shown in Figure 19-2. The map shows an asymmetric, nonorthogonal bow-tie appearance of irregular corneal astigmatism. The simulated keratometry values show 2.95 D of astigmatism at the steepest meridian of 130 degrees.

Combining this topographic information into the treatment module of the ASSORT program allows us to view the treatment and resultant spectacle and corneal astigmatism values that we are targeting (Figure 19-5). The amount of uncorrectable astigmatism, or ORA, in this patient's eye is 2.20 D Ax 34. The distribution of this is reflected in the Emphasis bar where 100% indicates a goal of completely eliminating refractive astigmatism and 0% shows the emphasis on completely reducing topographic astigmatism by the treatment.

If we treat conventionally, that is with 100% manifest refraction as shown in Figure 19-5, all of this ocular residual astigmatism will, in theory, remain neutralized on the cornea. This is shown as the Target 2.20 D at a meridian of 124 degrees—which is 90 degrees away from the ORA axis to neutralize the internal, noncorneal error, and results in the calculated zero astigmatism in the postoperative refraction (shown as the light blue Target). The target induced



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Topography Values

Pre-Op	45.56 48.51 @ 130

Corneal Astigmatism

Pre-Op	2.95 @ 130
Preference	0.00 @ 130
ORA	2.20 Ax 34
Target	0.00 @ 40

Spectacle Plane - Manifest

Corneal Plane - Manifest (BVD: 12.5)

TREATMENT: ST LAS PAR<10V2

		Sphere	Cylinder	Axis
INTENDED		-3.99	-2.95	40
Hyp Shift	0.00	-3.99	-2.95	40
Coefficient		1.00	1.30 Rot	0
ADJUSTED		-3.99	-3.83	40

Topography 100 % EMPHASIS Manifest 0 %

Topography 2.95 @ 130

ORA 2.20 Ax 34

Manifest 0.92 Ax -55

TIA Vector 2.95 Ax 40

Figure 19-6. The emphasis shown here relates to topography-guided treatment, where all the ORA (2.20 D) remains in the manifest refraction (100% topography/0% manifest refraction).

astigmatism vector (TIA) is the amount of astigmatism that we are attempting to correct, and is 0.92 D Ax 55.

At the other extreme, if we treat this eye emphasizing the reduction of topography values alone (Figure 19-6), −2.20 DC of the unavoidable residual ORA will theoretically remain in the postoperative refraction. Incorporating a proportion of each into the overall treatment, by shifting the emphasis for astigmatism reduction "to the left," increasing the proportion of complete corneal astigmatism correction, results in the treatment being more closely aligned to the principal corneal meridian, less "off axis" effect reduced corneal astigmatism and torque.[9]

Figure 19-2 shows the *optimal treatment* as determined from the surgical emphasis graph (Figure 19-7), which displays a linear relationship between the emphasis and the orientation of the target astigmatism. Figure 19-7 is based on the notion that with-the-rule astigmatism is favorable and against-the-rule astigmatism is unfavorable. In this example, the meridian of the target topography is 124 degrees. As it lies 34 degrees from a favorable, with-the-rule orientation of 90 degrees, 34 of 90 or 38% is apportioned to a topography-based goal of zero astigmatism. By the same process, the refractive astigmatism power axis of 34 degrees is 56 degrees away from 90 degrees and hence places 62% emphasis on the correction of refractive astigmatism. The resultant optimal TIA is displayed at the bottom right hand corner of Figure 19-2 and is positioned closer to the topographic TIA than to the refractive TIA. The target TIA here is slightly greater than before at 1.64 D Ax 45.

The overriding surgical principle is to approach corneal sphericity when the orientation of the target astigmatism becomes increasingly unfavorable. It is the surgeon's disgression to decide which orientation is more favorable than others and apportion the surgical emphasis accordingly using a linear relationship or other formula such as the square of the cosine of the target astigmatism meridian or axis.

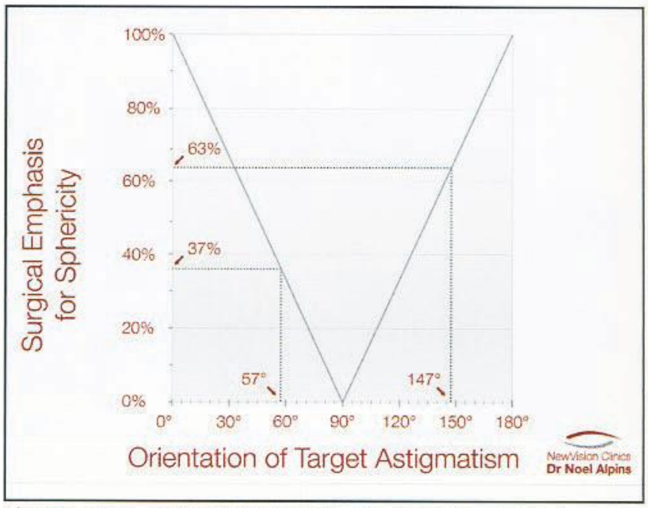

Figure 19-7. Linear relationship of surgical emphasis versus orientation of target topography based on notion that with-the-rule astigmatism is favorable and against-the-rule is unfavorable.

Note that the patient's ORA is still 2.20 D but it is apportioned between the refraction and the corneal readings. Here, less corneal astigmatism is targeted, with 62% of 2.20 (1.37 D) targeted at the same meridian of 124 and the remaining 38% (0.84 DC) of the emphasis placed refractively in a spherical equivalent of zero (+0.42 DS/−0.84 DC Ax 124). This remaining refractive astigmatism may not be fully perceptually evident to the patient. When measurements were in fact taken at 6 months simulated keratometry showed 1.25 D at 126 degrees while manifest refraction measured −0.25 DC Ax 45.

It is important to highlight that no matter what the percentage chosen on the Emphasis bar, the minimum amount of astigmatism that is being targeted is equal to the ORA. If the combined magnitude of the remaining astigmatism is greater than the initial ORA, the surgery then fails to achieve the maximum astigmatism treatment.

The fact is that even though all the astigmatism is not removable from the system, with some apportioned to the refractive astigmatism and the rest to the remaining corneal astigmatism, results with this technique were still significantly better than they would have been using conventional totally refractive techniques. The overall astigmatism was still reduced from 2.20 D, to be expected had refractive astigmatism been treated alone to 1.50 D (1.25 D corneal; +0.25 D manifest refraction).

This particular patient also had an improvement in best-corrected visual acuity (BCVA) from 20/20 to 20/15 (Table 19-1) as well as the improvement in uncorrected visual acuity (UCVA) from 20/200 to 20/20. This favorable outcome was common in many cases within a group of 45 eyes with form fruste or mild keratoconus that we studied.[2]

TABLE 19-1

Individual Outcomes of Example Patient With Irregular Astigmatism

Right Eye	*Unaided VA*	*BCVA*	*Manifest Refraction*	*Corneal Astigmatism (K)*
Preop	20/200	20/20	−3.00 DS/−1.00 DC x 55	2.95 D @ 130
Postop (3 months)	20/20	20/15	pl / −0.25 DC x 45	1.25 D @ 126

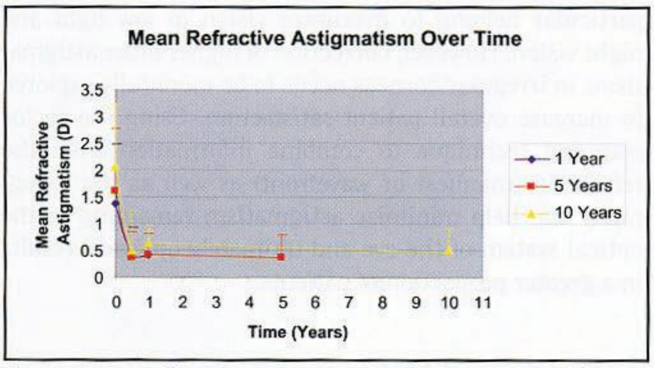

Figure 19-8. Refractive astigmatism stability over time for the 1-, 5-, and 10-year groups.

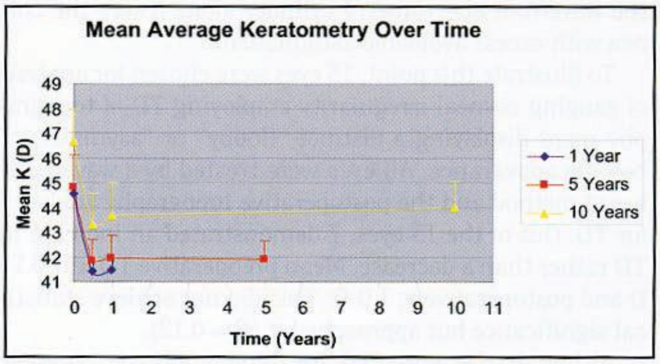

Figure 19-9. Stability of the cornea over time by consistency of mean keratometry values over time.

Outcomes

A group of 45 eyes with form fruste or mild keratoconus (nonprogressive) was treated using the Alpins Method of vector planning for the treatment of astigmatism. Treatments were performed on the VISX STAR S1 and subsequently VISX STAR S2 excimer laser systems. Due to the irregular shape of these corneas, as reflected by inferior/superior asymmetry of greater that 1.50 D on topography and higher than average ORA values with a mean of 1.34 D (compared with normal corneas where the ORA has been shown to be 0.73 D[5] and 0.81 D[1]), surface ablation with photo astigmatic refractive keratectomy (PARK) was performed in each case.

All treatments were optimized to leave minimum remaining corneal astigmatism favoring a with-the-rule orientation. Postoperative results at 12 months showed that, on average, we were able to reduce the corneal cylinder by an additional 0.68 D, compared to results that would have been attained by treating refractive values alone. This was achievable without compromising the refractive outcome.

UCVA at 1 year postoperatively showed 100% of eyes reached 20/40, 89% of eyes reached 20/30, and 56% of eyes reached 20/20. BCVA preoperatively and at 1 year was 89% reached 20/20 and 100% reached 20/30. Gains and losses in BCVA revealed an excess of gain over loss: 1 eye had 2 lines loss, 6 eyes 1 line loss, 22 eyes unchanged, 13 eyes had 1 line gain, and 3 eyes had 2 lines gain.

These eyes postoperatively have had a stable refraction (Figure 19-8) and corneal keratometry (Figure 19-9) over an extended period of time up to 10 years postoperatively for 9 of the eyes. This is true both in terms of nonprogression of disease and favorable spherical and astigmatic refractive outcomes. No problems or adverse signs such as increase in corneal irregularity and progression of ectasia resulting in a reduction of UCVA or BCVA were detected.

Vector Planning for Treatment of Irregular Astigmatism

Vector planning effectively minimizes total astigmatism (refractive + corneal) in regular and irregular astigmatism. In regular astigmatism a symmetrical bow-tie appearance on topography allows for an accurate calculation of a simulated keratometry. In cases of irregular astigmatism however an asymmetrical, nonorthogonal appearance of the topographic map places a line of 'best-fit' to calculate the simulated keratometry.

Current excimer laser technology not only disallows for the independent rotation of the second-order astigmatism from the higher-order aberrations used in vector planning, but is also incapable of asymmetrical treatments of astigmatism based on the 2 hemidivisions of the cornea.

Asymmetrical treatments in future can reduce astigmatism more effectively, treat both sides of cornea optimally, and reduce and regularize the astigmatism potentially improving best spectacle-corrected visual acuity

(BSCVA). There is a direct proportional relationship between increasing ORA and topographic disparity (TD).[19] This is a vectorial value for magnitude and axis calculating the separation between the 2 opposite semimeridian astigmatic values. This relationship was shown to be statistically significant in a group of 100 healthy astigmatic corneas prior to surgery.[19] It is therefore of crucial importance when treating irregular corneas that the topography values for astigmatism be incorporated into the treatment plan, as treatment based on the manifest refraction[1,2] or the wavefront aberrometry cylinder alone leaves the cornea with excess avoidable astigmatism.

To illustrate this point, 15 eyes were chosen for analysis of gauging corneal irregularity employing TD of topography maps displaying a distinct "floppy" or "asymmetric" bow-tie appearance. All eyes were treated by a wavefront-based method and the postoperative topography analyzed for TD. Out of the 15 eyes, 7 demonstrated an increase in TD rather than a decrease. Mean preoperative TD was 0.75 D and postoperatively, 1.0 D. This did not achieve statistical significance but approached it ($P = 0.12$).

Although the potential for high contrast, photopic Snellen 20/15 acuity, when achieved here, is considered a satisfactory outcome from refractive surgery, an associated reduction in low-contrast acuity and contrast sensitivity under mesopic conditions would reveal the benefit of a more regular corneal shape.

These eyes, in later life, may of course require cataract surgery, so the likely insertion of low aberration intraocular lenses, associated with any existing induced irregularity of the cornea, may limit the visual outcome of that surgery.

Patients evaluated for refractive laser surgery should be carefully selected[20,21] and followed over time to determine stability of manifest refraction and corneal topography to ensure any eye with progressive or unstable disease is excluded from elective surgical intervention. The risks associated with LASIK surgery in irregular corneas is well documented.[22] Photorefractive keratectomy, however, is a safe and effective means of treating such cases. Stability in both refractive and corneal measurements (with topography) over at least 2 years, corneal topography as a routine for all refractive laser surgery assessments looking for asymmetric bow-tie patterns together with a minimum age criterion of 25 years is recommended.

Conclusion

The Alpins method of vector planning utilizes information from both corneal and refractive data to target less postoperative corneal astigmatism and reduced torque. Using this combined approach, second- and third-order (coma and trefoil) astigmatic aberrations are minimized. As a result, there is the potential for improvement in BCVA and contrast sensitivity.

Neither of these 2 approaches at each extreme, either completely prioritizing topographic or refractive goals, can attain the same results in most astigmatic patients. Topographic-guided lasers play an important role in customizing treatments for irregular postoperative or traumatized corneas—enabling comprehensive mapping in situations where manifest/wavefront refractions may be inadequate to provide a smoother corneal surface.

Wavefront-guided laser refractive surgery has certainly been of benefit in correcting aberrations of the eye, in particular helping to maximize vision in low light and night vision. However, correction of higher order astigmatisms in irregular corneas needs to be more fully explored to increase overall patient satisfaction. Using the vector planning technique to combine information from the refraction (manifest or wavefront) as well as the topography can help minimize astigmatism remaining in the optical system of the eye and ultimately optimize results in a greater proportion of patients.

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