Treatment of irregular astigmatism

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ABSTRACT

Purpose: To treat irregular astigmatism by applying separate appropriate treatments in each of the two distinct hemidivisions of the cornea.

Setting: Cheltenham Eye Centre, Melbourne, Australia.

Methods: Two general surgical strategies are presented. The first applies the principles of optimization separately to each corneal hemidivision to achieve the maximum reduction in astigmatism when measured topographically and refractively. The second is for targeting symmetrical orthogonal topographic goals for each semimeridian to create the regular state in differing ways. These are performed in one of the following ways: without changing refractive astigmatism; by reducing the associated ocular residual astigmatism; by shifting the less favorably placed topography semimeridian to the other more favorably located one; by shifting both topographic semimeridians to more favorably located sites. This is an alternative when a potential improvement in the best corrected visual acuity is sought and the maximum reduction of astigmatism is not the priority.

Results: The calculated treatments necessary to achieve various improved astigmatic states, together with each of their respective separate refractive astigmatism targets, are presented. A single refractive astigmatism value for the entire cornea is also calculated by vector summation.

Conclusion: Consideration of each of the two distinct hemidivisions of the eye enables improved treatment of irregular astigmatism, potentially resulting in improved visual outcomes. *J Cataract Refract Surg 1998; 24:634–646*

The primary concern of the corneal surgeon is corneal shape; that is, the amount of astigmatism and its orientation in association with the aspheric cornea. The optimal treatment of astigmatism seeks to achieve less corneal astigmatism and to favorably influence the distribution of remaining astigmatism.[1,2]

Until now, conventional treatments have aimed for a surgical goal of zero astigmatism irrespective of whether the surgical method used was based on shape (corneal astigmatism) or function (refractive astigmatism). Previous papers[3,4] have recognized the inability to achieve both these goals because of the irreconcilable differences between refraction and topography. The concept of a target-induced astigmatism (TIA) vector[3] was therefore introduced to determine the expected target of the surgery being performed and provide the means to achieve any amount or orientation of corneal astigmatism.

The author has a financial interest in the subject matter.

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In the past, refraction has been the primary determinant for treatment of spherical and astigmatic refractive errors in excimer laser surgery. The introduction of topography provides significant advantages but also introduces unavoidable complexities. The advantages are a reduction in targeted corneal astigmatism by including shape parameters into the surgical plan[4] and the ability to use objective measurements for vectorial analysis of surgical results.[3]

One complexity is the difference between refractive astigmatism (R) and topography represented by the simulated keratometry value.[4] In general, this parameter, topographical astigmatism (T), is a mean value achieved over a number of measured constant reference points of the computer-assisted videokeratography (CAVK) map. The simulated keratometry value provided by CAVK is, however, a best-fit compromise and is derived in various ways by different devices.

In addition to the differences between R and T values, variances also exist in the dioptric magnitude of the astigmatism on each of the two parts, called hemidivisions, of the cornea. These differences are as prevalent as those between R and T. There may also be a nonorthogonal relationship between the two astigmatism values, the semimeridians, of each corneal division; that is, their axes on the cornea are often not aligned at 180 degrees to each other.

In practice, current topography technologies occasionally vary in their determination of the orientation of the simulated keratometry readings for nonorthogonal astigmatism. Any one of three axes on the same cornea may be selected: an orientation aligned with either one of the two nonorthogonal meridians or another intersecting the two.

The differences between the refraction and topography values cannot be dismissed as inconsequential.[4] Nor should it be suggested that an accurate and methodical refraction can resolve these differences, as the refractive astigmatism measures not only the corneal astigmatism but all the optical interfaces of the eye and the interpretation of the image by the cerebral cortex. Also, there is no mechanism to reconcile which of the two semimeridians of the irregular cornea may have been resolved with the manifest refractive astigmatism.

This paper details the controlled manipulation of corneal shape by asymmetrical surgical treatment to the differing nonorthogonal or asymmetrical hemidivisions of the cornea, allowing the achievement of any desired corneal shape.

Theory and Methods

The Designer Cornea® module of the Assort® refractive surgery planning computer program (using IBM-compatible 80486 DX personal computer with 8 megabytes of RAM) was used for calculating all parameters. These values are displayed in the boxes in the figures.

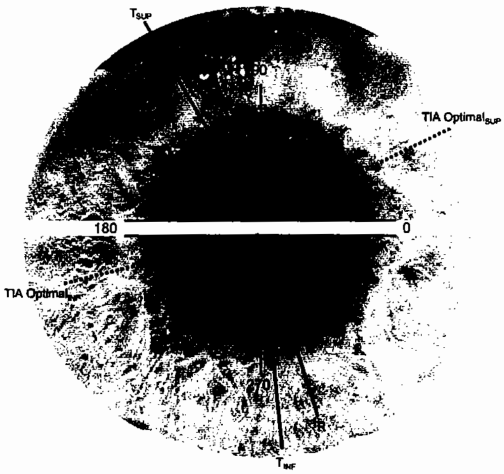
Definition of Irregular Astigmatism

The condition of irregular astigmatism of the cornea exists when the two steepest astigmatism meridians of the opposite hemidivisions differ; that is, where their magnitude values differ (asymmetry); they are not aligned at 180 degrees to each other (nonorthogonal); both conditions exist. The condition of corneal irregular astigmatism is quantified in diopters (D) as the topographic disparity (the vectorial difference between the two opposite semimeridian values for magnitude and axis in each corneal part) when displayed using a double-angle vector diagram (DAVD). Differences in topography values between the two divisions of the cornea are widely prevalent.

Applying the Optimal Treatment to Each Hemidivision

The optimal treatment of astigmatism occurs when the appropriate balance between the preoperative values of refraction and topography in the surgical plan is apportioned according to the orientation of the remaining astigmatism. In practice, the superior and inferior hemidivisions of the cornea will always share a common refractive value. However, when there are two distinct preoperative topography values on each hemidivision, there will be differing calculated target values of refractive and topographical astigmatism after asymmetrical treatment. The separate orientations of these upper and lower targets result in different emphases being placed on eliminating refractive or corneal astigmatism in the separate surgical plans for the two hemidivisions.

The optimal treatment example, which has been previously described,[4] is shown again on the superior cornea in Figure 1A. This polar astigmatism and surgi-



SUPERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.70 @ 120	+1.40 Ax 107	-1.40 Ax 17
TIA	1.56 Ax 26		
Target	0.28 @ 147	(+0.48 Ax 57)	(-0.48 Ax 147)
Emphasis	63%	37%	

AVERAGED TREATMENT VECTOR

		Plus Cylinder Refraction	Minus Cylinder Refraction
Preop		+1.40 Ax 107	-1.40 Ax 17
TIA_{Net}		1.46 Ax 20	
Target		+0.21 Ax 54	-0.21 Ax 144

INFERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.58 @ 277	+1.40 Ax 287	-1.40 Ax 197
TIA	1.43 Ax 194		
Target	0.41 @ 246	(+0.14 Ax 336)	(-0.14 Ax 246)
Emphasis	26%	74%	

Figure 1A. (Alpins) Treatment of irregular astigmatism by applying the optimal treatment to each corneal hemidivision; astigmatism and surgical vector diagram.

cal vector diagram shows the parameters as they would appear schematically on an eye. Using polar coordinates does not allow for the vectorial comparisons of astigmatism provided by the DAVDs (Figures 1B to 1D). In the two examples displayed on opposite parts (hemidivisions) of the cornea in Figure 1A, the emphasis in the surgical plan given to eliminating topographical astigmatism follows the linear relationship previously described.[4]

Figure 1B shows the separate superior and inferior topography targets by applying the TIA superior (optimal) to the superior cornea and the TIA inferior (optimal) to the inferior cornea. In this case, the closer the target astigmatism approaches against the rule, the more the surgical plan emphasizes topography to achieve a spherical cornea in that part. Which orientations of corneal astigmatism are considered favorable and which unfavorable is the surgeon's decision.

When treatment differs between the two hemidivisions of the cornea, a separate calculation is required to determine the combined effect on refractive astigmatism of the differing TIAs. Summation of the treatment vectors (Figure 1C) is required for asymmetrical treatment of astigmatism. The change in refractive astigmatism becomes the vectored sum (or average) of the two treatment components of superior and inferior hemidivisions. This average value is then applied to the common refractive astigmatism value in both hemidivisions (Figure 1D) to determine the average refractive astigmatism value for the eye.

The bracketed values for refractive astigmatism in the boxes displaying superior and inferior astigmatism values are calculated separately for each corneal hemi-

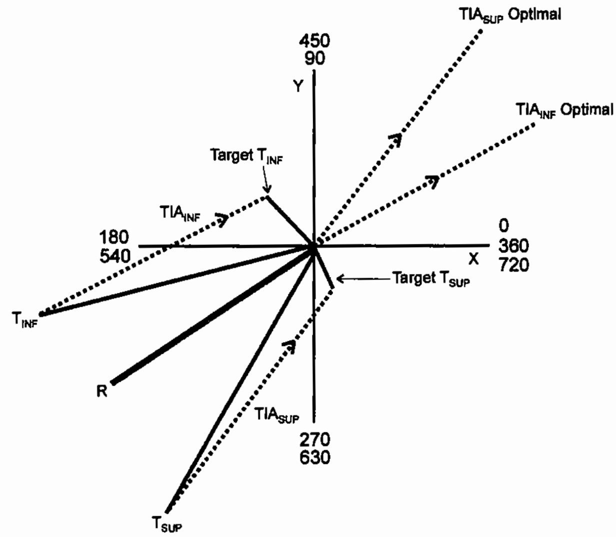


Figure 1B. (Alpins) Treatment of irregular astigmatism by applying the optimal treatment to each corneal hemidivision; double-angle vector diagram.

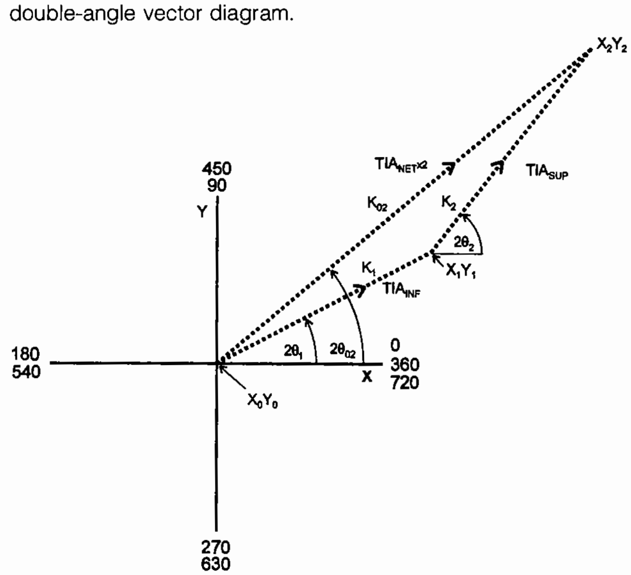


Figure 1C. (Alpins) Summation of treatment vectors for average treatment; double-angle vector diagram.

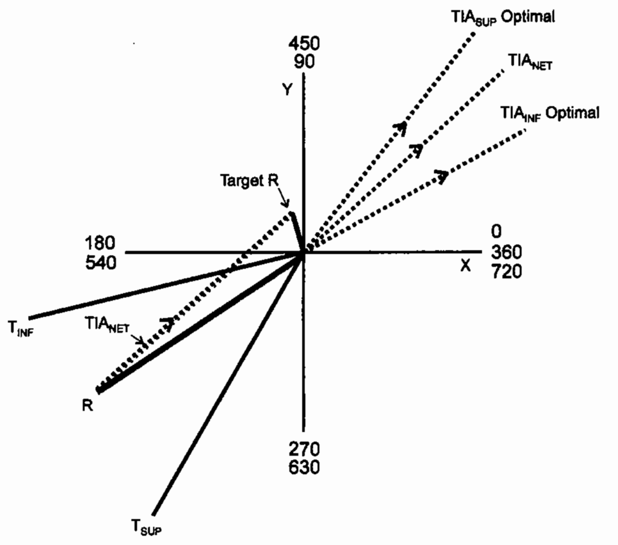


Figure 1D. (Alpins) Treatment of irregular astigmatism by applying the optimal treatment separately for each corneal hemidivision; double-angle vector diagram.

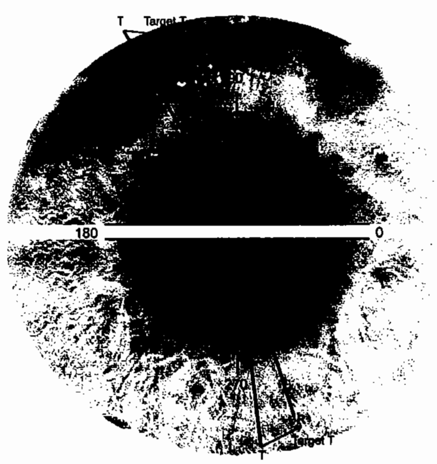
division (Figure 1A). This is achieved by applying the superior TIA to the preoperative refractive astigmatism to determine the superior refractive astigmatism target (R_{SUP}), and the same process with the inferior TIA for the inferior target (R_{INF}). Two refractive astigmatism values cannot be perceived by one eye, and only summated values are shown in Figure 1D. However, calculated values for each hemidivision are displayed in brackets (in gray) and on the diagram (fine dark lines) (Figure 1A).

In this example, the orientation of these two refractive values, which are separated by almost 90 degrees, results in the single averaged R-value calculated from the summated treatment vector being smaller than the sum of the two individual refractive astigmatism components (R_{SUP} and R_{INF}) (Figure 1A).

Achieving Orthogonal Symmetrical Astigmatism with No Change in Refractive Astigmatism

In the presence of nonorthogonal astigmatism, asymmetrical astigmatism, or both, there may be a desire to regularize the corneal shape, providing the opportunity for improved uncorrected visual acuity (UCVA) or best corrected visual acuity (BCVA). It would be advantageous to be able to perform this task without a net change in the spherical or astigmatic refractive condition.

Figures 2A to 2C show that by treating the cornea as two independent parts for the desired change in topographic astigmatism, the required amount of astigmatic change can be applied equally at the appropriate meridians at right angles to each other (Figure 2A), which is in the opposite (180 degrees) vectorial orientation (Figure 2B). The existing topographical astigmatism can be targeted to coincide in both magnitude and meridian (actually 360 degrees apart) on the DAVD (Figure 2B) to create the orthogonal symmetrical state (180 degrees apart) on an astigmatism diagram of the eye (Figure 2A). For this example, the vector topographic disparity (TD) is (1.29 D axis 61 degrees) displayed in Figure 2B. The magnitude of the TD is the dioptric distance between the displays of superior and inferior topographical values on a 720 degree DAVD.



SUPERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.70 @ 120	+1.40 Ax 107	-1.40 Ax 17
TIA		0.65 Ax 61	
Target	1.51 @ 109	(+1.52 Ax 94)	(-1.52 Ax 4)

AVERAGED TREATMENT VECTOR

		Plus Cylinder Refraction	Minus Cylinder Refraction
Preop		+1.40 Ax 107	-1.40 Ax 17
TIA$_{Net}$		0.00 Ax	
Target		+1.40 Ax 107	-1.40 Ax 17

INFERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.58 @ 277	+1.40 Ax 287	-1.40 Ax 197
TIA		0.65 Ax 331	
Target	1.51 @ 289	(+1.60 Ax 299)	(-1.60 Ax 209)

Figure 2A. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism and no change in refractive astigmatism; astigmatism and surgical vector diagram.

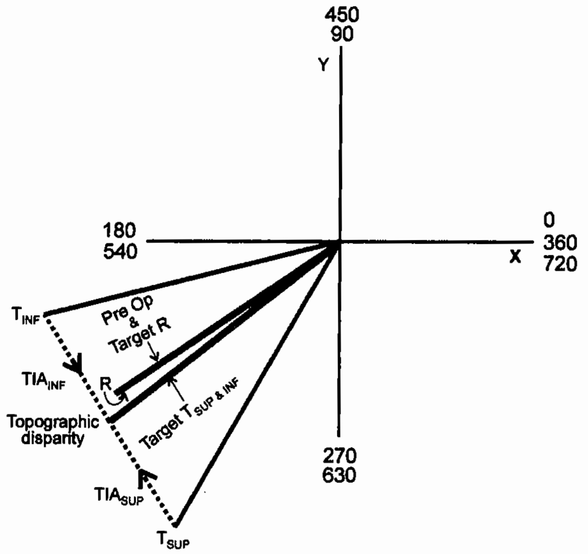


Figure 2B. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism and no change in refractive astigmatism; double-angle vector diagram.

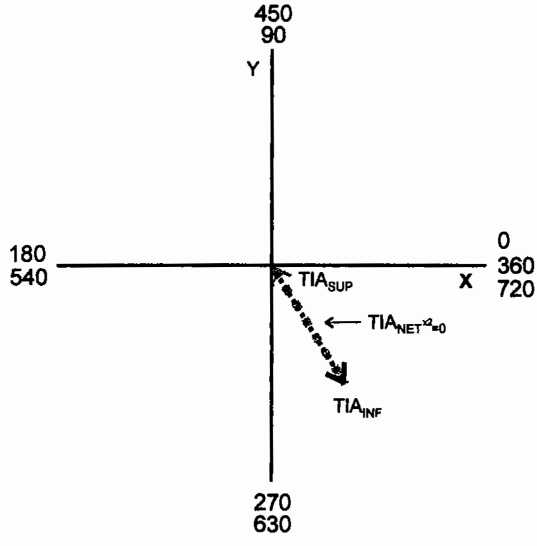


Figure 2C. (Alpins) Summation of treatment vectors; double-angle vector diagram.

Two axes can describe the orientation of the TD: the orientations of one of the two minimum treatments to correct the disparity, moving T sup toward T inf (TIA_{SUP}) or T_{INF} toward T_{SUP} (TIA_{INF}). To establish a convention for the axis of TD, the orientation of this vector is from superior to inferior on the DAVD (Figure 2B). These two axes of TD lie at 90 degrees to each other on an astigmatism diagram of the eye and are the same axes as the two equal minimum treatments necessary to create the regular state (Figure 2A) without a refractive astigmatism change.

In the common situation in which one topography semimeridian lies in the superior hemidivision of the cornea (0 to 180 degrees) and the other in the inferior (180 to 360 degrees), it is clear which is T_{SUP} and which is T_{INF}. Occasionally, both semimeridians may lie above or below the 0 to 180 degree division boundary of the cornea. In this case, the topography semimeridian that has the least angular separation from the 90 degree meridian in either a clockwise or counterclockwise direction is the superior topography semimeridian and the other the inferior. If their angular separation from 90 degrees is the same, the one with the longer magnitude is the superior.

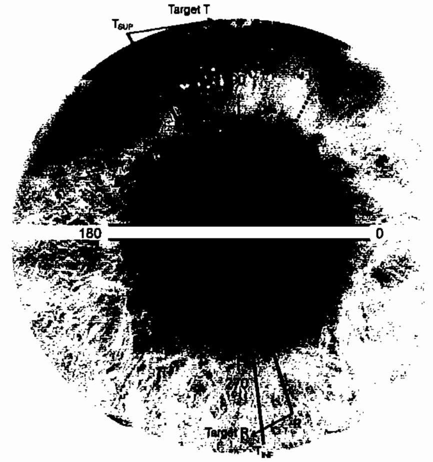
Summation of the two treatment vectors of equal magnitude and opposite (180 degrees) vectorial directions (Figure 2C) show that the two TIAs negate each other's effect, so the net TIA is zero. Thus, the average treatment has no net effect on refractive astigmatism.

Suboptimal vision associated with irregular astigmatism may improve BCVA vision by regularizing the cornea. When there is also no change in spherical equivalent, there is no change in the overall refractive status of the eye; thus, no change in spectacles, if worn, would be necessary.

Achieving Orthogonal, Symmetrical Astigmatism by Shifting One Topography Semimeridian

The correction of irregular astigmatism to produce an orthogonal symmetrical state may be achieved by treating a single hemidivision of the cornea, as shown in Figures 3A and 3B. Moving the less favorable to coincide with the more favorably placed astigmatism, which in this example is closer to a with-the-rule (WTR) orientation (at 180 degrees/540 degrees on the DAVD), improves the orientation of the shifted superior semimeridian of the corneal astigmatism and the refractive astigmatism.

In this case, regularity is produced with astigmatic change to only one hemidivision of the cornea. The net TIA effect, which is half the vector sum of the single treatment, is applied to the refractive astigmatism (Figure 3C). No change to the inferior topographic semimeridian is targeted. The alternative correction of



SUPERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.70 Ax 120	+1.40 Ax 107	-1.40 Ax 17
TIA	1.29 Ax 61		
Target	1.58 Ax 97	(+1.87 Ax 85)	(-1.87 Ax 175)

AVERAGED TREATMENT VECTOR

		Plus Cylinder Refraction	Minus Cylinder Refraction
Preop		+1.40 Ax 107	-1.40 Ax 17
TIA_{Net}		0.65 Ax 61	
Target		+1.52 Ax 94	-1.52 Ax 4

INFERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.58 Ax 277	+1.40 Ax 287	-1.40 Ax 197
TIA	0.00 Ax		
Target	1.58 Ax 277	(+1 40 Ax 287)	(-1 40 Ax 197)

Figure 3A. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism by shifting one topography hemimeridian to coincide with the more favorably placed one; astigmatism and surgical vector diagram.

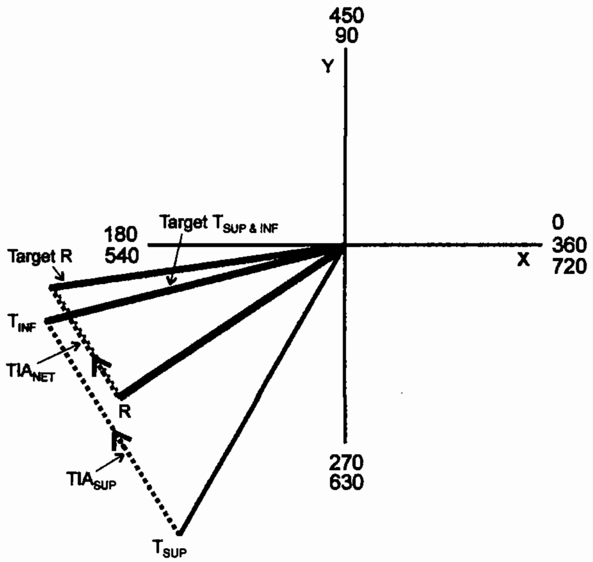


Figure 3B. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism by shifting one topography hemimeridian to coincide with the more favorably placed one; double-angle vector diagram.

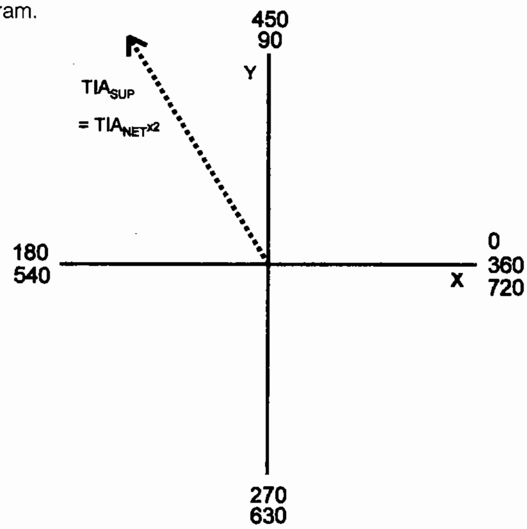


Figure 3C. (Alpins) Summation of treatment vectors; double-angle vector diagram.

the irregularity could also be achieved by shifting the other topography semimeridian by treatment 90 degrees away in the other hemidivision. The treatments shown in Figures 2 and 3 are the minimum total treatments required to regularize the cornea and equal the magnitude of the TD.

A study was done to evaluate the TD and related parameters in the first treated eye of 100 consecutive patients who had excimer laser photoastigmatic keratectomy between June 1992 and October 1995. Corneal topography values were determined by the simulated keratometry values using the TMS topographic modeling system (Computed Anatomy Inc.). The separate upper and lower semimeridian values were derived from the normalized zonal astigmatic statistic plots using the two steepest and their respective flattest values at the 5.0 mm optical zone of the cornea. The mean TD in the sample group was 1.10 D ± 0.08 (SEM) (range 0.04 to 4.70 D). The TD exceeded 1.00 D in 43 patients.

Scatterplots of TD values in those 100 eyes were graphed against other variables that exist in corneas with some amount of irregularity. This is shown in Figures 4 to 7 and 9 to determine where there is a demonstrable relationship between TD, a vectorial measure of corneal irregularity, and each variable.

Topographic disparity versus topography magnitude difference. The scatterplot of the magnitude of the TD compared with the difference between superior and inferior topographic magnitude values in the 100 eyes shows a close relationship between the values (Figure 4).

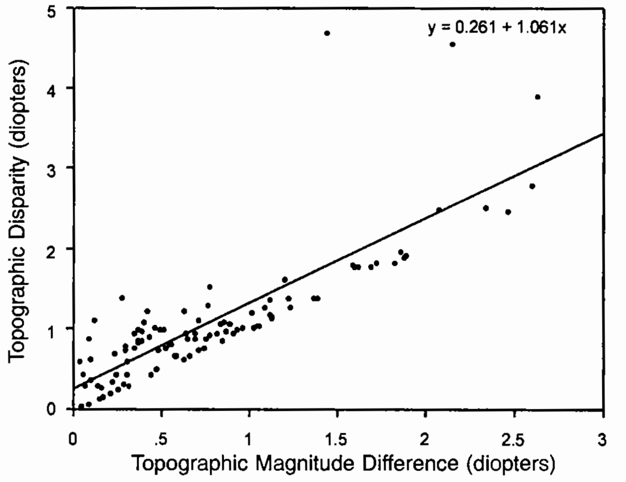


Figure 4. (Alpins) Topographic disparity magnitude versus the difference between superior and inferior topographic magnitude values (r = .825; P < .0001).

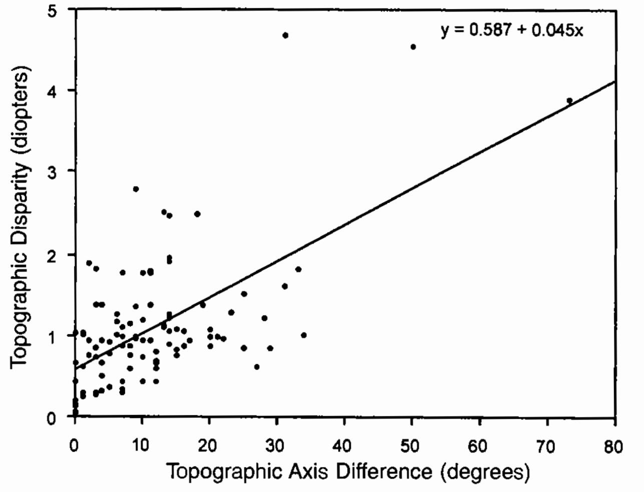


Figure 5. (Alpins) Topographic disparity magnitude versus nonorthogonal angle subtended between topography semimeridians (r = .617; P < .0001).

Topographic disparity versus topography nonorthogonal angle. When the two semimeridian topography orientations are not aligned, an angle exists between their extensions from their intersection into the other hemidivision of the cornea. The greater this angle, the more severe the nonorthogonal state. When this angle is zero, the relationship of the superior to the inferior corneal astigmatisms forms a straight line and is orthogonal. A significant relationship also existed between the TD values in the 100 eyes and the nonorthogonal angle subtended between upper and lower semimeridians (Figure 5).

Topographic disparity versus meridian of simulated keratometry. Some relationship was seen between the TD magnitudes and the axis of the simulated keratometry value for each of the 100 eyes as determined by topography (Figure 6).

Topographic disparity magnitude versus TD axis. No definite relationship was seen between the TD magnitude and its calculated axis value in each of the 100 eyes (Figure 7).

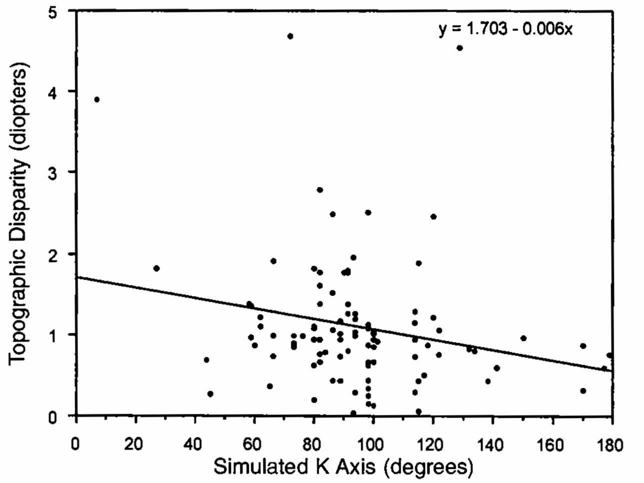


Figure 6. (Alpins) Topographic disparity magnitude versus meridian of simulated keratometry (r = .223; P = .0258).

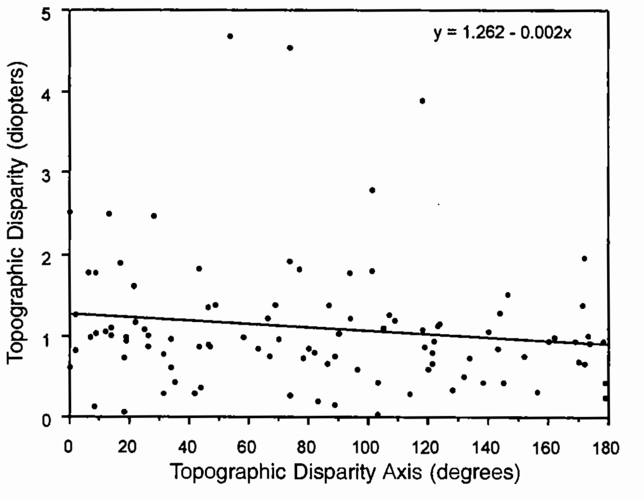
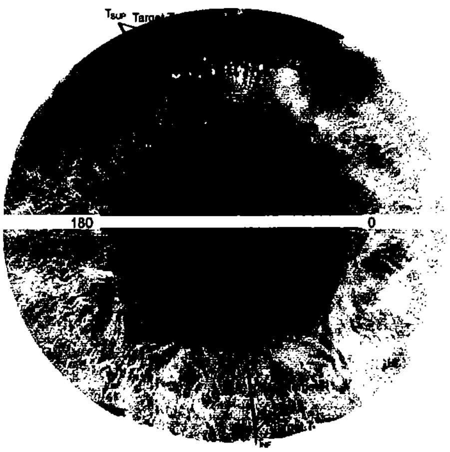


Figure 7. (Alpins) Topographic disparity magnitude versus topographic disparity axis (r = .133; P < .1881).

Achieving Orthogonal Symmetrical Astigmatism and Reduced Ocular Residual Astigmatism

Another method to improve the topographic astigmatism of the eye is rendering it orthogonal and symmetrical by targeting the refractive astigmatism magnitude and axis for the topography values in both hemidivisions of the cornea (Figures 8A and 8B). This



SUPERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.70 @ 120	+1.40 Ax 107	-1.40 Ax 17
TIA		0.76 Ax 57	
Target	1.40 @ 107	(+1.50 Ax 92)	(-1.50 Ax 2)

AVERAGED TREATMENT VECTOR

		Plus Cylinder Refraction	Minus Cylinder Refraction
Preop		+1.40 Ax 107	-1.40 Ax 17
TIA Net		0.14 Ax 38	
Target		+1.30 Ax 105	-1.30 Ax 15

INFERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.58 @ 277	+1.40 Ax 287	-1.40 Ax 197
TIA		0.55 Ax 338	
Target	1.40 @ 287	(+1.43 Ax 298)	(-1.43 Ax 208)

Figure 8A. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism and minimum ocular residual astigmatism; astigmatism and surgical vector diagram.

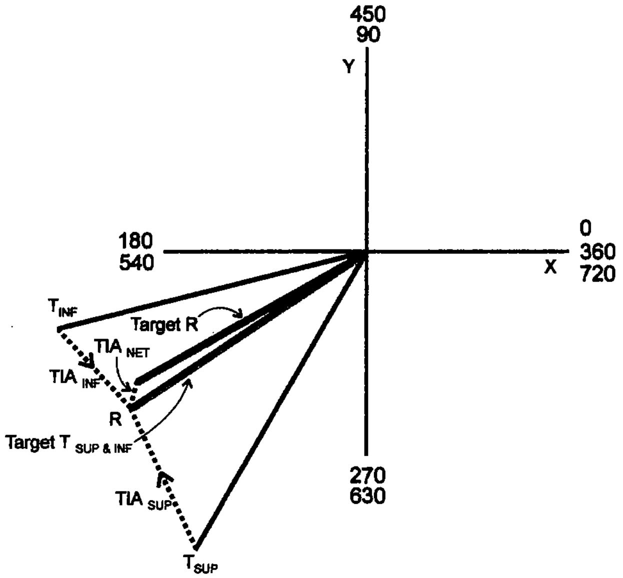


Figure 8B. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism and minimum ocular residual astigmatism; double-angle vector diagram.

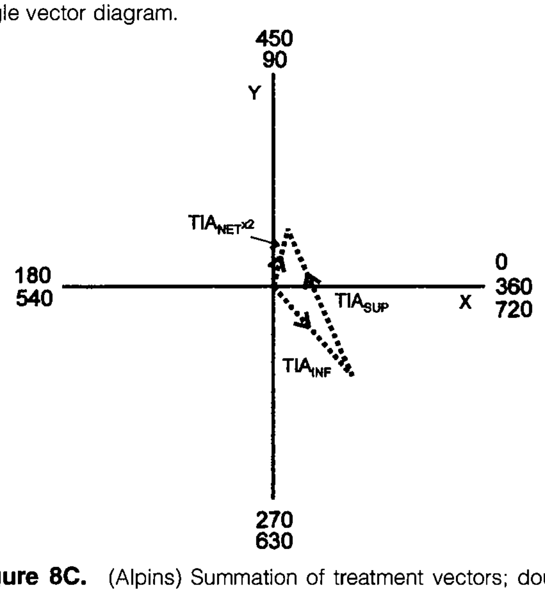


Figure 8C. (Alpins) Summation of treatment vectors; double-angle vector diagram.

will result in a net reduction in the ocular residual astigmatism (ORA) from the decrease in the difference between topography and refraction in each corneal part. The refractive astigmatism induced by the net TIA change will shift (as determined by summating the superior and inferior treatment vectors) (Figure 8C). The resultant ORA of both hemidivisions will be equal and at reduced levels.

Ocular residual astigmatism magnitude versus TD magnitude. As corneal irregularity increases, it is likely that the separation between the refractive astigmatism axis and one or both topographical meridians will also increase. Manifest refraction was determined as previously described.[4] The scatterplot in Figure 9 shows that a relationship exists between the magnitudes of TD and the ORA. The mean ORA in the 100 eyes was 0.91 D ± 0.06 (SEM) (range 0.06 to 4.90 D). The ORA exceeded 1.00 D in 41 eyes.

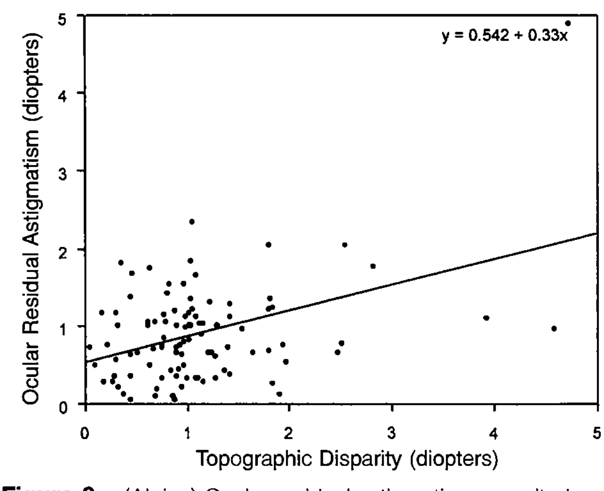


Figure 9. (Alpins) Ocular residual astigmatism magnitude versus topographic disparity magnitude ($r = .415$; $P < .0001$).

Achieving Orthogonal Symmetrical Astigmatism in a Preferred Orientation

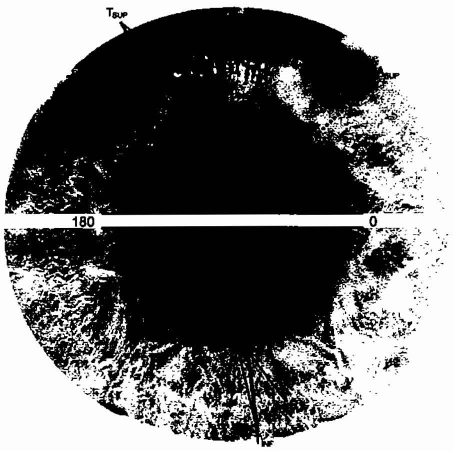
The TIA can be set to change the prevailing refractive or topographic astigmatism for any desired or favorable orthogonal symmetrical targets. In this example, both semimeridians of the cornea are targeted at 0.75 D in a WTR orientation (90 and 270 degrees) to render the cornea regular at a preferred axis and magnitude (Figures 10A and 10B). Summating the treatment vectors (Figure 10C) shows that in this case, there is a net favorable shift in the refractive astigmatism, with a corresponding reduction in its magnitude (Figures 10A and 10B).

Achieving Nominated or Desired Corneal Astigmatism: Generic Vector Diagram for Hemidivisional Change

Any change in astigmatism can be examined in its separate component parts on each hemidivision of the cornea.

1. Asymmetrical change can be induced by applying ablation patterns of different shapes on the separate parts of the cornea. This achieves two independent astigmatic goals on each part of the cornea, creating the potential to achieve any pattern of regular or irregular astigmatism.

2. Intrastromal changes can be induced by holmium heat induction, intrastromal ablation, or con-



SUPERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.70 @ 120	+1.40 Ax 107	-1.40 Ax 17
TIA		1.48 Ax 43	
Target	0.75 @ 90	(+1.27 Ax 74)	(-1.27 Ax 164)

AVERAGEO TREATMENT VECTOR

		Plus Cylinder Refraction	Minus Cylinder Refraction
Preop		+1.40 Ax 107	-1.40 Ax 17
TIA_{Net}		1.03 Ax 32	
Target		+0.72 Ax 84	-0.72 Ax 174

INFERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.58 @ 277	+1.40 Ax 287	-1.40 Ax 197
TIA		0.87 Ax 193	
Target	0.75 @ 270	(+0.56 Ax 293)	(-0.56 Ax 203)

Figure 10A. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism with orientation shifted to a WTR orientation; astigmatism and surgical vector diagram.

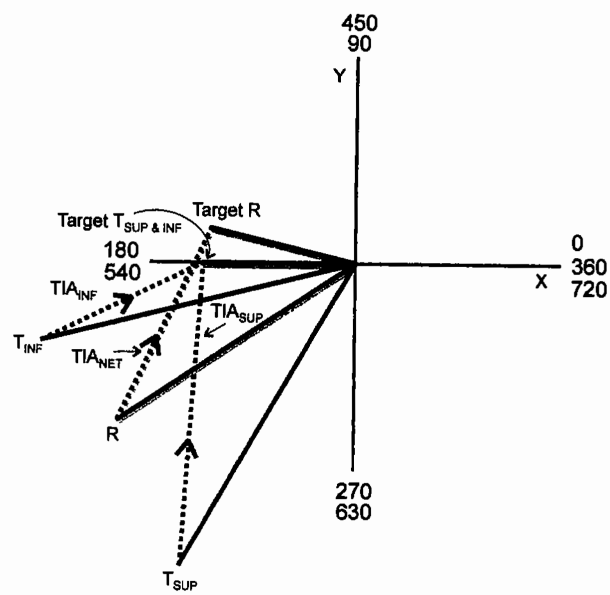


Figure 10B. (Alpins) Treatment to achieve orthogonal symmetrical astigmatism with orientation shifted to a WTR orientation; double-angle vector diagram.

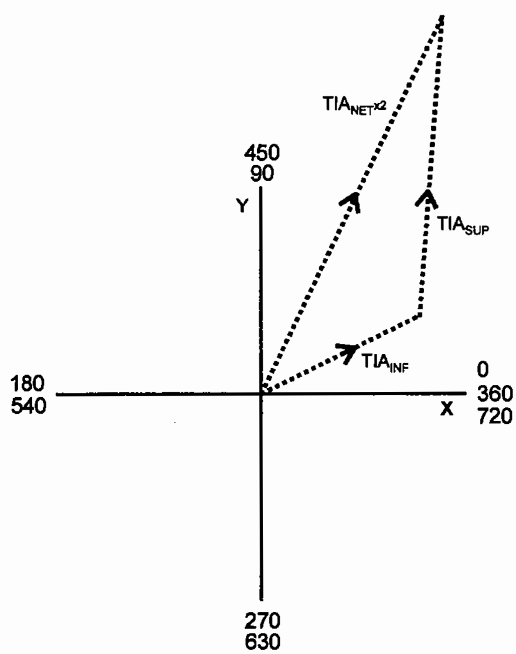
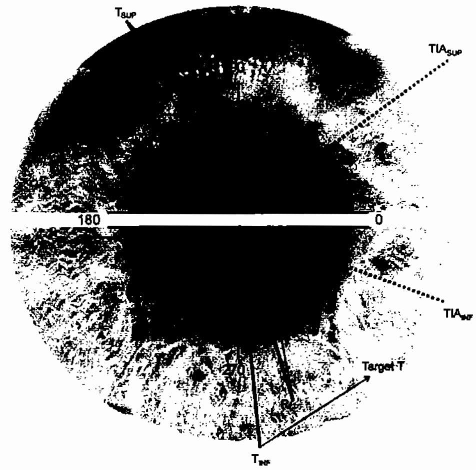


Figure 10C. (Alpins) Summation of treatment vectors; double-angle vector diagram.



SUPERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.70 @ 120	+1.40 Ax 107	-1.40 Ax 17
TIA		2.00 Ax 36	
Target	0.50 @ 60	(+1.25 Ax 58)	(-1.25 Ax 148)

AVERAGEO TREATMENT VECTOR

		Plus Cylinder Refraction	Minus Cylinder Refraction
Preop		+1.40 Ax 107	-1.40 Ax 17
TIA_{Net}		1.05 Ax 11	
Target		+0.43 Ax 122	-0.43 Ax 32

INFERIOR

	Topography	Plus Cylinder Refraction	Minus Cylinder Refraction
Preop	1.58 @ 277	+1.40 Ax 287	-1.40 Ax 197
TIA		1.88 Ax 340	
Target	1.50 @ 310	(+1.88 Ax 317)	(-1.88 Ax 227)

Figure 11A. (Alpins) Treatment to achieve any nominated or desired corneal astigmatism—an example of random asymmetrical targets; astigmatism and surgical vector diagram.

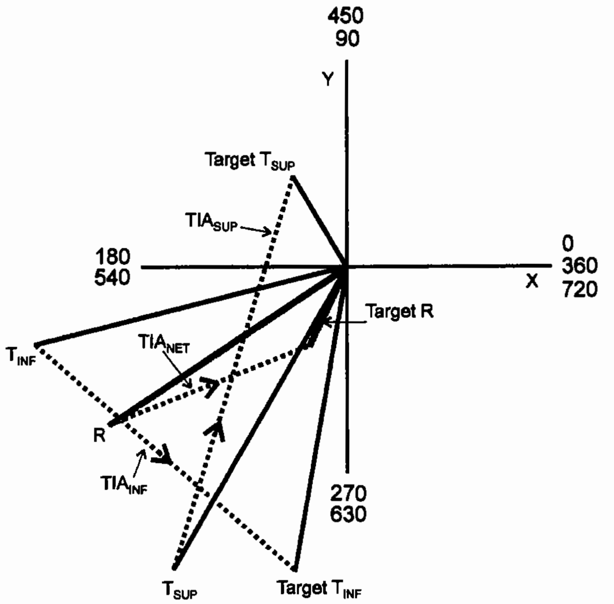


Figure 11B. (Alpins) Treatment to achieve any nominated or desired corneal astigmatism—an example of random asymmetrical targets; double-angle vector diagram.

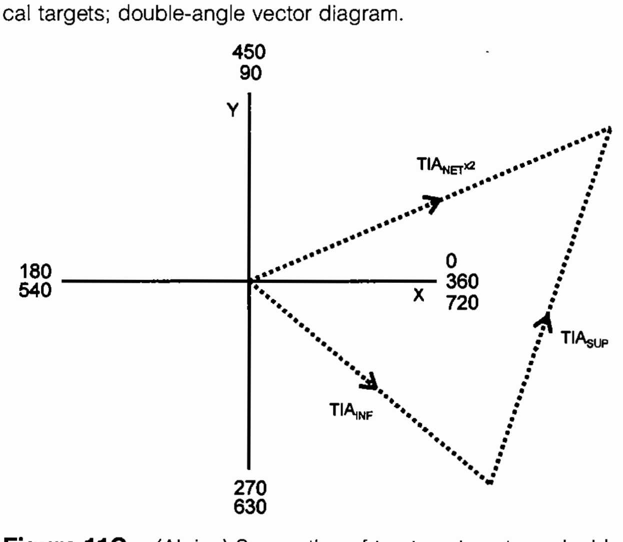


Figure 11C. (Alpins) Summation of treatment vectors; double-angle vector diagram.

ductive keratoplasty (radiotherapy) to cause local destruction of tissue and a net contraction and steepening of the cornea at that orientation. This may be applied asymmetrically to each side of the cornea.

3. Astigmatic keratotomy incisions can be placed in an asymmetrical pattern at 90 degrees to the desired axis of steepening.

Any targeted corneal astigmatism can, theoretically, be achieved with the appropriate hemidivisional targeted change in astigmatism (i.e., the TIA). In Figure 11A, the target astigmatisms of both hemidivisions represent any two chosen targets; the two TIAs have been separately calculated to modify the cornea in the required fashion. The net TIA change in refraction is calculated by averaging the opposite hemidivisional TIAs, which is one half the total summated treatment (Figure 11C).

Only one subjective manifest response of the eye can be perceived so that only one refractive astigmatism value can be measured. The average targeted astigmatism change, the net TIAs, can be determined by the summation of the two individual treatments applied to the separate corneal hemidivisions (Figure 11B).

The target refraction values can be determined by vectorially adding this net TIA to each preoperative refractive value. These are displayed overlapping each other, to coincide in magnitude, and separated by 360 degrees in axis when represented on opposite sides of the cornea in a 720 degree DAVD (Figure 11B).

Discussion

A quantitative and qualitative evaluation of the videokeratography corneal map usually shows some irregularity between the two topographic semimeridians. This occurs because the magnitudes of the two sides of the bow-tie representation on the contour map differ, their orientations are unaligned, or both. To achieve the most favorable treatment of irregular corneal astigmatism,[4] separate treatment plans are required for each topographic magnitude and axis value with its common refractive astigmatism value. The different minimum target astigmatisms for each part of the cornea can then be calculated and their orientations used to determine an optimal TIA for that side.[4] This dual semimeridian solution is relevant regardless of the incisional or nonincisional techniques used.

Benefits of Considering Dual Semimeridian Solutions

Recognizing the inevitable differences that exist between the shapes of the two topographic corneal halves allows us to determine the optimal treatment according to the individual shape of each part of the eye. Using the optimal treatment for each hemidivision of the cornea may result in an enhanced synergistic effect in reducing overall targeted refractive astigmatism over the result achieved when the cornea is treated symmetrically.

The treatment of irregular astigmatism to achieve an orthogonal symmetrical state can be achieved by using further techniques that vary the asymmetrical treatment of each hemidivision of the cornea. This separation of treatment of the astigmatism of the eye into hemidivisions changes the orientation of the two semimeridian corneal astigmatisms.

Two equal treatments can be applied at right angles to each other, negating each other's refractive effect (Figure 2A). In this way, the use of opposing vectorial forces can realign nonorthogonal asymmetrical semimeridians to achieve a coincident and therefore regular relationship (Figure 2B) while leaving the refractive astigmatism unchanged. This is achieved with the minimum total treatment possible.

The rotation of the less favorable corneal semimeridian toward the other more favorably placed side will achieve a better alignment of topography and in most cases a more favorable rotation of the refractive astigmatism (Figure 3), also with the minimum possible treatment.

The differences between topography and refraction can be reduced on one or both semimeridia by each targeting the preoperative refractive astigmatism. Improvement is achieved by a closer alignment of the refractive and topographic astigmatism; the net induced change in refractive astigmatism will equal the remaining reduced ORA in that eye (Figure 8). Both topography meridians can be targeted to a chosen favorable orientation and magnitude with a concurrent improvement in the orientation and amount of refractive astigmatism (Figure 10).

The treatment of astigmatism may be directed at correcting existing aberrations of corneal shape. In this manner, any degradation in the clarity of the retinal image caused by the prevailing corneal irregularities could be improved. This astigmatic change can occur independent of or at the same time as inducing spherical change.

The regularizing of nonorthogonal and asymmetrical elements of corneal astigmatism, with or without a change in refractive astigmatism, could potentially improve BCVA and UCVA. This treatment could be applied by ablative or intrastromal lasers, incisional keratotomy, or a combination. It may be useful for treating amblyopia ex anopsia in children or in adult eyes with irregular astigmatism that are not functioning at their full potential.

One might anticipate that a significant proportion of eyes with reduced vision is likely to coexist with a combination of nonorthogonal or asymmetrical astigmatisms. The correction of this aberrant state at any age, by treatment of the cornea as two dissimilar parts, could improve the quality and quantity of vision perceived by that eye.

Keratoconus

The spectrum of physiological aberrations of corneal shape extends from high degrees of astigmatism to the subclinical levels of keratoconus, which appear as forme fruste and early types,[5] are now more frequently identified with the aid of CAVK technology. Astigmatism in family members of patients with keratoconus is frequently asymmetric, with the power inferior to the corneal apex more often exceeding the power superior to the apex than the reverse.[6]

The fine line that divides what lies inside and outside of the physiological spectrum may well be determined by clinical signs such as excessive corneal steepening, apical thinning, or scarring. The differing patterns found in keratoconus may represent a continuum of different stages in the progression of the topographic alterations that occur over time in keratoconus.[6] On careful examination of the topographical maps in eyes with keratoconus change, there is often a vestigial remnant of one half of the bowtie indicating the presence of both semimeridians of the astigmatism, even when in a grossly asymmetrical state.

It is possible that lower grades of keratoconus could benefit from differential flattening and steepening on the opposite semimeridian to reduce or eliminate the existing asymmetry of the condition. Reducing these irregularities on asymmetrical corneas that exist in association with keratoconus may improve UCVA and BCVA.

Qualitative Surgical Planning

This paper has stressed the importance of the quantitative information derived from CAVK; however, the value of further qualitative information that can be derived from this quantitative planning and analysis technique should also be recognized. The method can be used in a predictive manner by applying the targeted change in astigmatism (either symmetrical or differing between the two hemidivisions) to the preoperative astigmatism state.

In principle, the calculated predicted appearance can be displayed on a videokeratography map by vectorially calculating the effect of the treatment at each preoperatively measured topography point, recontouring the map, and displaying the effect of the proposed treatment. In this way, an analysis of the proposed treatment's effect can be determined in a quantitative pictorial display during the planning process. Similarly, a value for the target refractive astigmatism can also be determined in accordance with the summation of the proposed treatment vectors (Figures 1C to 3C, 8C, 10C, and 11C).

Surgical planning can be finely tuned according to the appearance of the topography based on the calculated targeted change. For example, when optimally treating astigmatism, small increases or decreases in emphasis to eliminate refractive or topographic astigmatism on the upper or lower treatment vector (TIA) will change the target topographic appearance. These changes may vary according to the surgeon's qualitative criteria of a favorable result and will concurrently alter the target refractive astigmatism.

Zero or close-to-zero refractive astigmatism can be achieved with asymmetric corneal treatments without either treatment vector, separately or individually, targeting zero refractive astigmatism as calculated for that hemidivision. This might give greater emphasis to the correction of topographical astigmatism in both parts of the cornea while achieving the benefit of targeting less overall refractive astigmatism.

Further alternatives to fine-tuning the treatment, when not maximizing the correction of astigmatism,[4] can be achieved for either of the two treatment vectors by separately increasing or decreasing the treatment to induce more or less flattening effect, or altering the torque effect by rotating the treatment.[7] This can also be performed under a real-time display of the intended topography that would result from any alteration of the treatment plan.

Vector Change Maps

After surgery, the postoperative and the preoperative topography maps can be compared by examining the change map, as is currently performed by simple arithmetic change, or using a vectorial change analysis at each point. This pictorial vector analysis could be done for all relevant analysis parameters by various vector change map displays.

For example:

1. The correction index change map would provide the relative areas of undercorrection and overcorrection of the treatment.
2. Correction could also be expressed in terms of positive and negative amounts of magnitude of error.
3. Absolute success could be displayed as the difference vector change map.
4. Relative success could be displayed as the index of success change map.
5. Variations in alignment or misalignment could be shown by mapping variations as the angle-of-error change map.

The information gained by generating point-by-point vectored change can be used for individual or groups of patients to improve the performance of the refractive surgical tool used.

In time, the current separate disciplines of CAVK and laser modulation of the corneal shape can merge as an integrated entity for the control and evaluation of the surgical procedures where separate meridional changes in corneal shape are performed. The eventual coupling of these complementary and interdependent technologies of diagnosis, analysis, and treatment can only synergistically enhance each of their individual values in the correction of refractive errors.

Conclusion

Recognizing and addressing the differences between not only topography and refractive astigmatism but also the two topography semimeridian values of the cornea is an essential step to realizing the maximum potential vision for an astigmatic eye.

Treatments applied to the opposite sides of the cornea deliberately unaligned with the steepest topographic axes provide the theoretical basis for changing the relative shape of the cornea in various ways. The ability to achieve orthogonal and symmetrical topographic astigmatism, affecting the refractive astigmatism in a favorable way or not changing it at all, enables a potential and significant expansion in the means to produce astigmatic enhancement and make improved visual performance possible.

Producing the orthogonal symmetrical state by separately applying astigmatic treatment to each part of the cornea will create regularity of topographic astigmatism, which may improve the quality of the perceived image on the retina. This methodology provides a blueprint for the controlled manipulation of corneal shape under topographic control to achieve any desired change. Furthermore, it presents a means for ultimately achieving the merging of diagnostic (corneal topography), analytic (vector analysis), and therapeutic (laser device) refractive surgery tools into one integrated functional unit.

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Appendix

Abbreviations

TIA	=	target induced astigmatism
TIA_{SUP}	=	target induced astigmatism in superior hemidivision of cornea
TIA_{INF}	=	target induced astigmatism in inferior hemidivision of cornea
TIA_{NET}	=	averaged refractive astigmatism treatment vector
TIA_{INF} Optimal	=	optimal treatment vector for inferior hemidivision of cornea
TIA_{SUP} Optimal	=	optimal treatment vector for superior hemidivision of cornea
T	=	topographical astigmatism
T_{SUP}	=	topographical astigmatism in superior hemidivision of cornea
T_{INF}	=	topographical astigmatism in inferior hemidivision of cornea
R	=	refractive astigmatism
R_{SUP}	=	refractive astigmatism in superior hemidivision of cornea
R_{INF}	=	refractive astigmatism in inferior hemidivision of cornea

Figure Legend

....	=	vector
- - - - -	=	orientation line
______	=	astigmatism