Chapter 15 Photoastigmatic refractive keratectomy (PARK)

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INTRODUCTION: DEFINING THE PROBLEM

Previous chapters have shown how the 193 nm excimer laser can treat myopia. However, a majority of patients seeking excimer laser photorefractive surgery for myopia have concomitant astigmatic refractive errors. In our experience, patients with moderate myopia (less than 5.0 D) averaged 1.04 D of associated cylinder at the corneal plane, while the high myopes (greater than 5.0 D but less than 10.0 D) averaged 1.20 D and the extreme myopes (greater than 10.0 D) 1.39 D. In order to achieve the goals of emmetropia, optimal uncorrected visual acuity, and maximum patient satisfaction, the refractive surgeon must address the problem of astigmatic errors. This chapter will review the role of the excimer laser in combating astigmatism.

Astigmatism can be one of the most difficult and frustrating problems in refractive surgery. First one must precisely quantify the astigmatism that is to be treated. Astigmatism can be measured objectively at the corneal plane via keratometry or corneal topography, or subjectively based on manifest refraction. The surgeon must weigh several options in deciding how to individualize treatment for each case. Moreover, ocular surgery in general, as well as refractive surgery, can create its own unintended induced astigmatic changes—Surgical Induced Astigmatism (SIA) vector.

ASTIGMATISM: SURGICAL AND OPTICAL CONCEPTS

Astigmatism is defined optically as 'the refractive anomaly in which no point focus is formed owing to the unequal refraction of the incident light by the dioptric system of the eye in different meridians'.[1] Curvature astigmatism of the anterior corneal surface occurs physiologically. The average normal cornea has a difference in refractive power between its principal meridians of 0.5–0.75 D, with a difference of 1.0 D being the upper limit of normal. 'Regular' astigmatism occurs when the principal meridians are at right angles to each other on the topographical map and equal in magnitude. Most younger people have the axis of least curvature in the horizontal plane and the axis of steepest curvature in the vertical plane. This has been termed 'with-the-rule' astigmatism. With age there is usually a gradual shift of axis, with a steepening of the horizontal and flattening of the vertical meridian, a configuration called 'against-the-rule' astigmatism.

However, the net 'refractive' astigmatic error is not entirely derived from an asymmetric anterior corneal surface. The posterior surface of a normal cornea usually shows an astigmatic error that varies from 0.25 to 0.5 D. The principal meridians of the posterior corneal astigmatism are usually opposite in orientation to the anterior surface, and partially neutralize the astigmatic error. There is also curvature astigmatism on both surfaces of the lens. These again usually have the greater curvature in the horizontal meridian and partially negate the anterior corneal astigmatism. In addition, the laminated zones of the lens are not always concentric and may vary considerably in their refractive indices. This variance in refractive power in different meridians induces a small net astigmatism. Astigmatism also arises from the decentering of the optical system. None of the optical surfaces of the eye is geometrically centered around the visual axis or has a true axis of symmetry. The fovea is not on the optical axis, but is usually situated 1.25 mm inferiorly to the temporal side; meanwhile, the central pupillary line and optical axis are generally eccentric to the nasal side of the cornea. Furthermore, there is usually some degree of inherent tilting of the retina. Following Gullstrand's model of 1911 which accepts an angle of 5° between the pupillary line and optical axis, there would be 0.1 D of astigmatism that exists as the result of the alignment of the optical axis with a 2 mm pupil. Finally, the visual cortical perception of the transmitted image can influence the readings that are measured by the subjective manifest refraction.

The astigmatism that is measured by the manifest refraction is the 'refractive astigmatism'. The astigmatism that is measured on the anterior corneal surface by topography is the 'topographical astigmatism'. The disparity between the refractive astigmatism as measured at the corneal plane and the topographical (or keratometric) astigmatism is the 'residual astigmatism'. The residual astigmatism is the sum of the effect of the astigmatic errors present on the posterior corneal surface, the lens surfaces and varying refractive indices of the media, and from decentration of the optical system. The residual astigmatism can be determined by vectorially subtracting the values of the topographical astigmatism from the refractive astigmatism at the corneal plane, or its magnitude can be measured directly by performing a subjective refraction with a spherical hard contact lens on the cornea. If the excimer laser were to create a spherical anterior corneal surface, the patient's residual astigmatism would remain as the refractive astigmatism. If the excimer laser is used to sculpt all the refractive astigmatism onto the cornea, then the topographical astigmatism remaining on the cornea would equal the residual astigmatism both in magnitude and axis, and would neutralize the astigmatism from the other refractive components of the eye.

Over a large series it was found that young adults averaged 1.04 D of corneal astigmatism and 0.61 D of residual astigmatism.[2] Some degree of detectable refractive astigmatism was found in 95% of eyes. The most common form of astigmatism was compound myopic (39%), with compound hypermetropic astigmatism (27%) being the next most frequent; simple hypermetropic (14%), mixed astigmatism (11%) and simple myopic astigmatism (10%) were slightly less common.

The amount of astigmatism varies greatly. Approximately 85% of people have less than 1.25 D of refractive astigmatism. An increase in spherical error is associated with a larger astigmatic error as mentioned above. Astigmatism results in both blurring and distortion of the visual image. Regular astigmatism, with the principal steep and flat meridians at right angles to each other, results in no single focused retinal image, but has two separate lines at right angles to each other, with an intervening ellipse of least confusion that has a diameter proportional to the degree of astigmatism (Figure 15.1). In hyperopic and mixed astigmatism, the patient will generally attempt to focus one of the lines

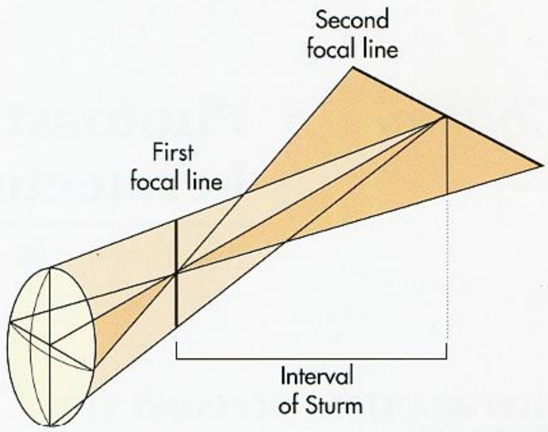


Figure 15.1 *Schematic of the Conoid of Sturm demonstrating that a spherocylindrical lens produces two focal lines separated by the interval of Sturm.*

via accommodation, preferring to have a distorted rather than blurred image. The myopic astigmatic patient will be unable to compensate with accommodation and will have a perpetually blurred image for distance vision. The adverse effect on uncorrected visual acuity, at least in terms of recognizing Snellen letters, is least for with-the-rule astigmatism, less for against-the-rule and perhaps greatest when the astigmatism is oblique. This will be discussed in more detail when we turn to surgical planning.

One diopter of astigmatic error will, on average, decrease uncorrected acuity to the level of 20/30 or 20/40 depending on the axis (versus 20/50 for 1.00 D of spherical myopia or absolute hyperopia.)[3] Other than simply blurred vision, astigmatism can cause glare, asthenopia, distortion, eye strain, headaches, monocular diplopia, a head tilt with neck pain from attempting to change an oblique axis closer to vertical, and continual squinting in an unconscious attempt to create a stenopeic slit to view only the paraxial rays of one meridian.

ADDRESSING THE PROBLEM: CONSIDERATIONS FOR PLANNING THE PROCEDURE

The refractive surgeon who wishes to provide optimal uncorrected vision has to address the complexities of

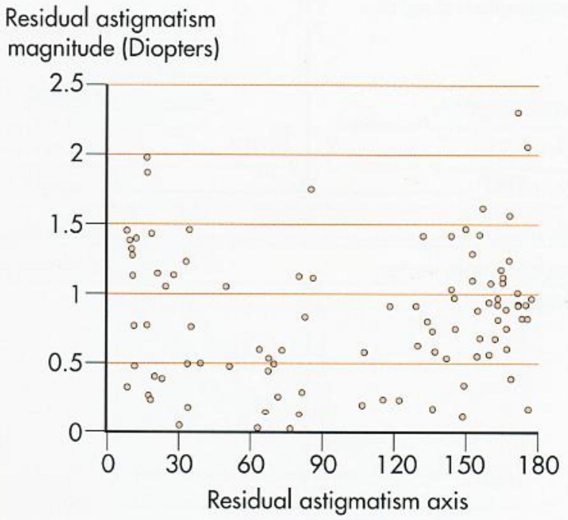
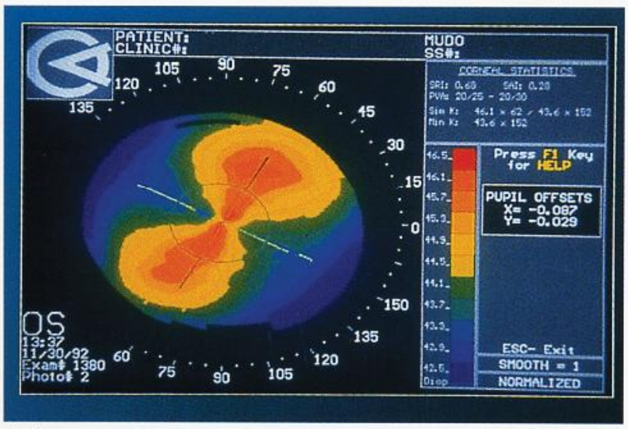


Figure 15.2 *Scatterplot of residual astigmatism: axis versus magnitude for 100 consecutive patients.*[38]

astigmatic errors. The corneal shape must be incorporated with the refraction into a specific surgical plan. This can best be done with vector analysis.[4] The first priority is to identify the goal of the treatment for each individual's eye according to the preoperative parameters of topography and refraction. Subjective refraction, modified if necessary by cycloplegic findings, and corneal topography are both obtained. Simply creating a spherical anterior corneal surface, guided by topography, will leave the residual error from the posterior surface of the cornea, the lens and decentration of the axis. This resultant astigmatism is often in an against-the-rule or oblique orientation, and it can be difficult for the patient to adapt to the new axis. However, using the refractive astigmatism, and sculpting a spherocylindrical lens into the cornea without regard for the sphericity of the cornea, may cause spherical aberration which increases in corneas with larger amounts of astigmatism.[5]



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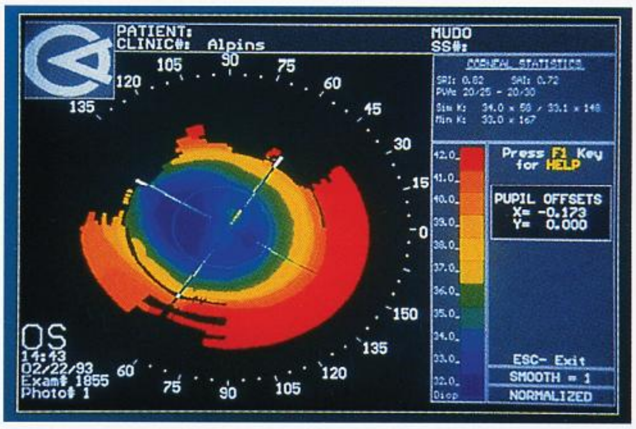

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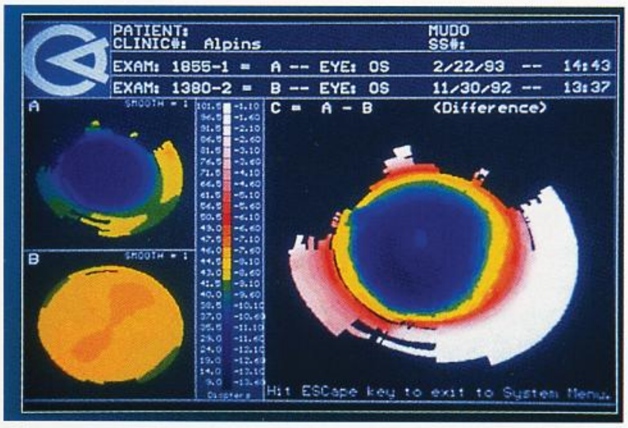

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Figure 15.3 *Computerized corneal topographic maps. (a) Before PARK treatment showing bow tie regular astigmatism. (b) After PARK treatment showing uniform curvature of the central cornea. (c) Subtraction map showing the astigmatic change produced by the laser.*

The targeted final astigmatism is determined from the differences in the refractive and topographical astigmatism. As has been previously stated, 'with-the-rule' astigmatism is preferable to other orientations. Having the steepest meridian oriented vertically, in a case of simple astigmatism, places the clearest retinal image in the vertical meridian. Eggers has shown that this improves visual acuity as measured by Snellen type, as vertical strokes predominate in the English alphabet.[6] In addition, the nasotemporal overlap of ganglion cells that supply both optic tracts are bilaterally cortically represented. They lie on the vertical midline raphe of retinal receptors and neuronal fibers, centered on the fovea, with a width extending greater than 1° of arc.[7] This explains the much lower stereoscopic threshold for vertical objects than those oriented in any other meridian.

In eyes that have lost their accommodative powers, such as occurs in pseudophakia, it may also be advantageous to have a small amount of residual 'with-the-rule' astigmatism in association with a mild amount of myopia. Sawusch and Guyton calculated the cross-sectional area of Sturm's conoid for a schematic eye for given refractive errors and at fixed distances.[8] They found the optimal astigmatic error needed to obtain maximal depth of focus and least theoretical blur for any given spherical equivalent refractive error. The optimal depth of focus was obtained when the plus cylindrical component equalled the negative sphere minus 0.25 D, for example, +0.50D –0.75D × 180°. They then correlated these results with 10 pseudophakic patients who had better than 20/40 (6/12) Snellen uncorrected visual acuity for both near and distance vision.

In a personal series of 100 consecutive patients who underwent photorefractive astigmatic keratectomy, the calculated mean residual astigmatism of the group as determined by vector analysis was 0.81 D with a range of 0.01–2.32 D (Fig. 15.2). The residual astigmatism exceeded 1.00 D in 34 patients, and seven of these exceeded the preoperative magnitude of topographic astigmatism (simulated keratometry) as measured by videokeratography. In the surgical planning process, the surgeon should decide on the optimal manner in which to deal with the residual astigmatism. Using the dual guiding refractive principle that it is more favourable to have less corneal astigmatism with a bias to maintaining a with-the-rule orientation, the surgeon can choose to leave a calculated amount of residual astigmatism in the manifest refraction and reduce the amount of targeted corneal astigmatism. If the target spherical equivalent is achieved within range, the patient will no longer require spectacles but will benefit from less resultant corneal astigmatism.

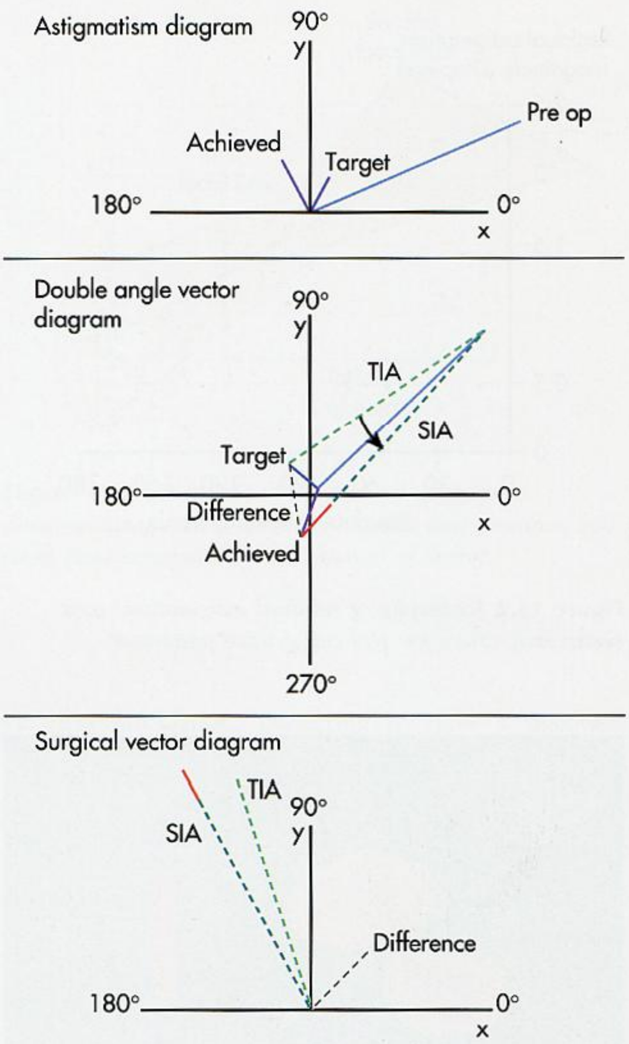

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Figure 15.4(*a*) *Alpins' method of vector analysis utilizing doubled angles to calculate the surgical vector of change in astigmatism.*[4]

Once the desired topographic and refractive targets have been chosen, a calculation is made to determine the desired targeted change in astigmatism in the corneal curvature. The force required to effect this change from the preoperative topographic and refractive condition is termed the 'Target Induced Astigmatism (TIA) vector'. The actual path taken is the SIA. This is the vector representing the actual change that occurs. By using the targeted corneal

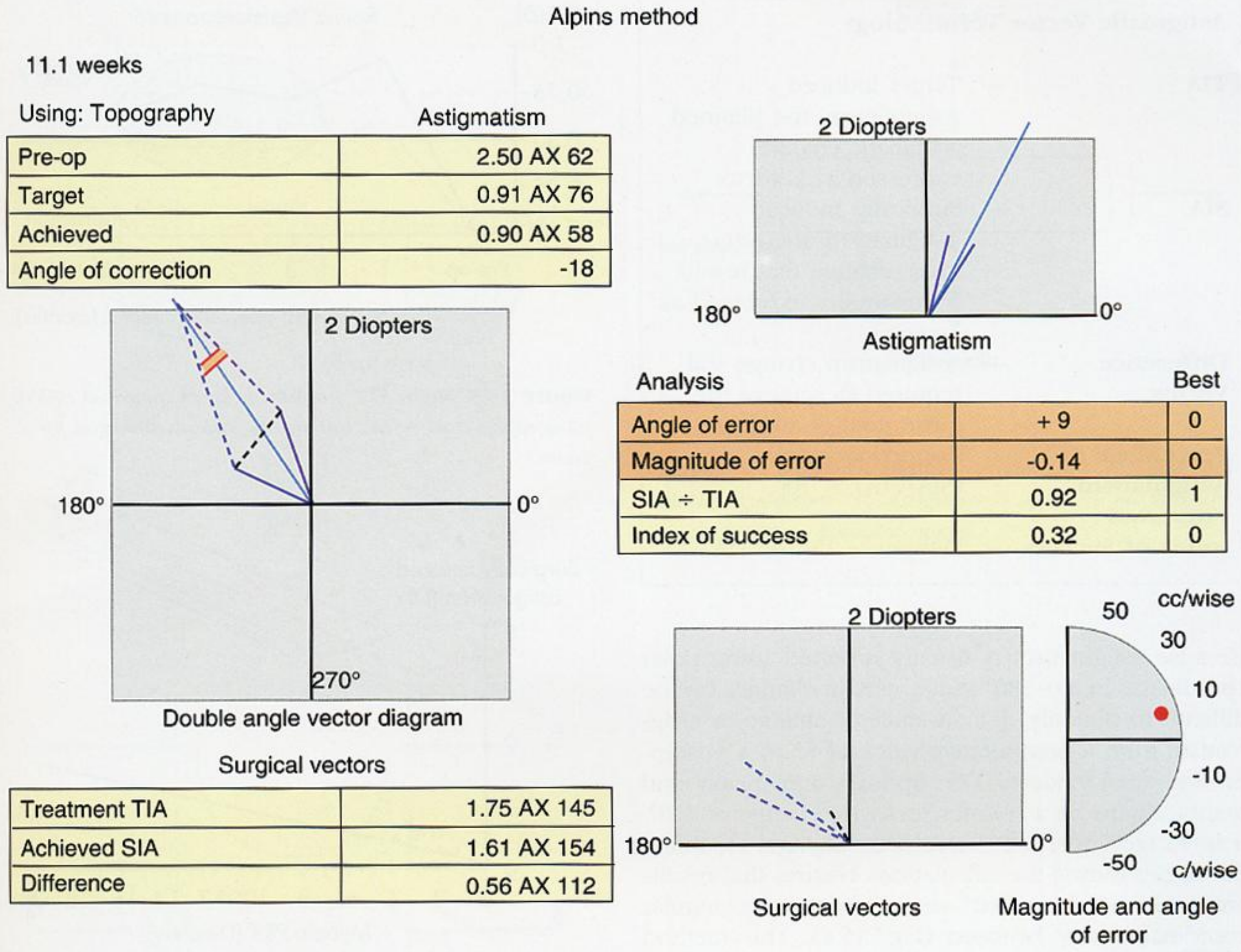

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Figure 15.4 *(b) Vector analysis applied to the case shown topographically in Figure 14.3.*

astigmatism instead of one of the two preoperative astigmatism values, all astigmatism surgeons can operate under a single paradigm with parallel goals set on the optimal targeted result of surgery.[4,38]

Analyzing astigmatism results by topography as well as refraction is an essential step to enable the objective as well as the subjective evaluation of the results of the procedure. It is the various relationships between the SIA and the TIA that provide the necessary information as to whether too much or too little change was applied, how to adjust for it, and whether the treatment was on axis or off axis (Fig. 15.3). A topographic subtraction map is useful in demonstrating the point-by-point change in astigmatism, but it does not provide vector analysis of the changes.

Vector analysis enables the refractive surgeon to examine his or her results in no more complex a manner than a golfer analyzing his or her putting on a flat green. Was the ball hit too firmly or too softly? Was it on axis, or was it misdirected in a clockwise or counter-clockwise direction? If the hole was missed on the first putt, how long must the second putt be to land in the hole (the Difference Vector) and how does this length compare to the length of the first putt (Index of Success)?

Astigmatic Vector Terminology

TIA	— Target Induced Astigmatism, the planned astigmatic change expressed as a vector.
SIA	— Surgically Induced Astigmatism, the astigmatic change that results from surgery expressed as a vector.
Difference Vector	— Astigmatism change still required to achieve the initial goal of surgery.
Percentage of Astigmatism Corrected	— Correction Index (SIA/TIA) × 100.
Index of Success	— Difference Vector/TIA.

Because astigmatism is usually reported using polar coordinates in a 0–180° sense, certain changes can be difficult to quantify. For instance, a change in astigmatism from a preoperative value of 5° to a postoperative equal value of 175° appears numerically and graphically to be a counterclockwise change of 170°. It is, in fact, only a 10° clockwise change. Doubling the angles during the calculations ensures that results are examined in a 360° sense, so that rectangular coordinates may be used (Fig. 15.4). This method simplifies interpretation of changes between preoperative, desired, and achieved astigmatic values and is necessary to determine the magnitude and direction of surgical vectors.

It is important to assess how effective a treatment has been, that is how close the SIA is to the TIA. This will depend on the computer algorithm used for the laser, proper and steady centration and uniform epithelial healing. Remodelling of the anterior corneal surface may also result in changes in the astigmatic status. Spherical photorefractive keratectomy does not intend to induce astigmatism. However, the SIA from treating purely myopic refractive errors with spheric treatment zones is about 0.5 D by refraction and 0.6 D by topography at 12 months in our patients (Fig. 15.5). Alpins and Taylor reported a mean induced astigmatic change of 0.45 D in 42 eyes one year after spherical PRK treatments,[9] and Goggin and his associates report a mean cylinder power change of 0.75 D in 60 eyes.[10] Nine eyes had greater than 1.00 D of SIA. Tabin et al report a linear relationship, with increased inadvertently induced astigmatism with the treatment of increasing amounts of spherical myopia (Fig. 15.6).[11] This inadvertent SIA must be considered when planning excimer laser surgery.

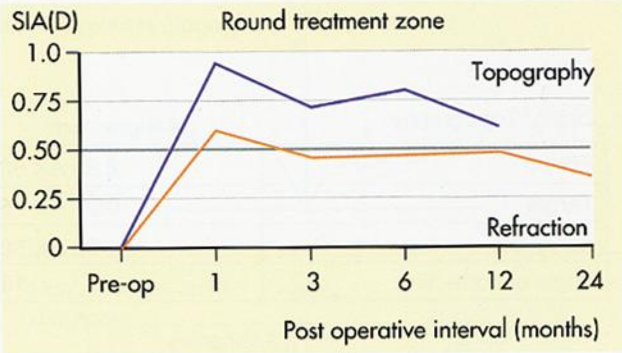

Figure 15.5 *Mean SIA magnitude after spherical PRK by topography and refraction in 60 patients followed for 2 years.*[9]

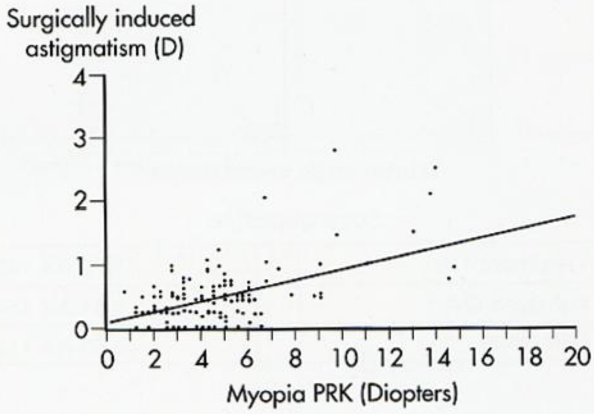

Figure 15.6 *SIA magnitude plotted against the amount of preoperative myopia for 155 PRK patients at 1-year follow-up: note the increasing inadvertently induced astigmatism with the treatment of larger amounts of myopia.*[11]

HOW IT WORKS: THE WAY VARIOUS EXCIMER LASERS CORRECT ASTIGMATISM

The first description of how the excimer laser can be used to create toric ablations for the correction of

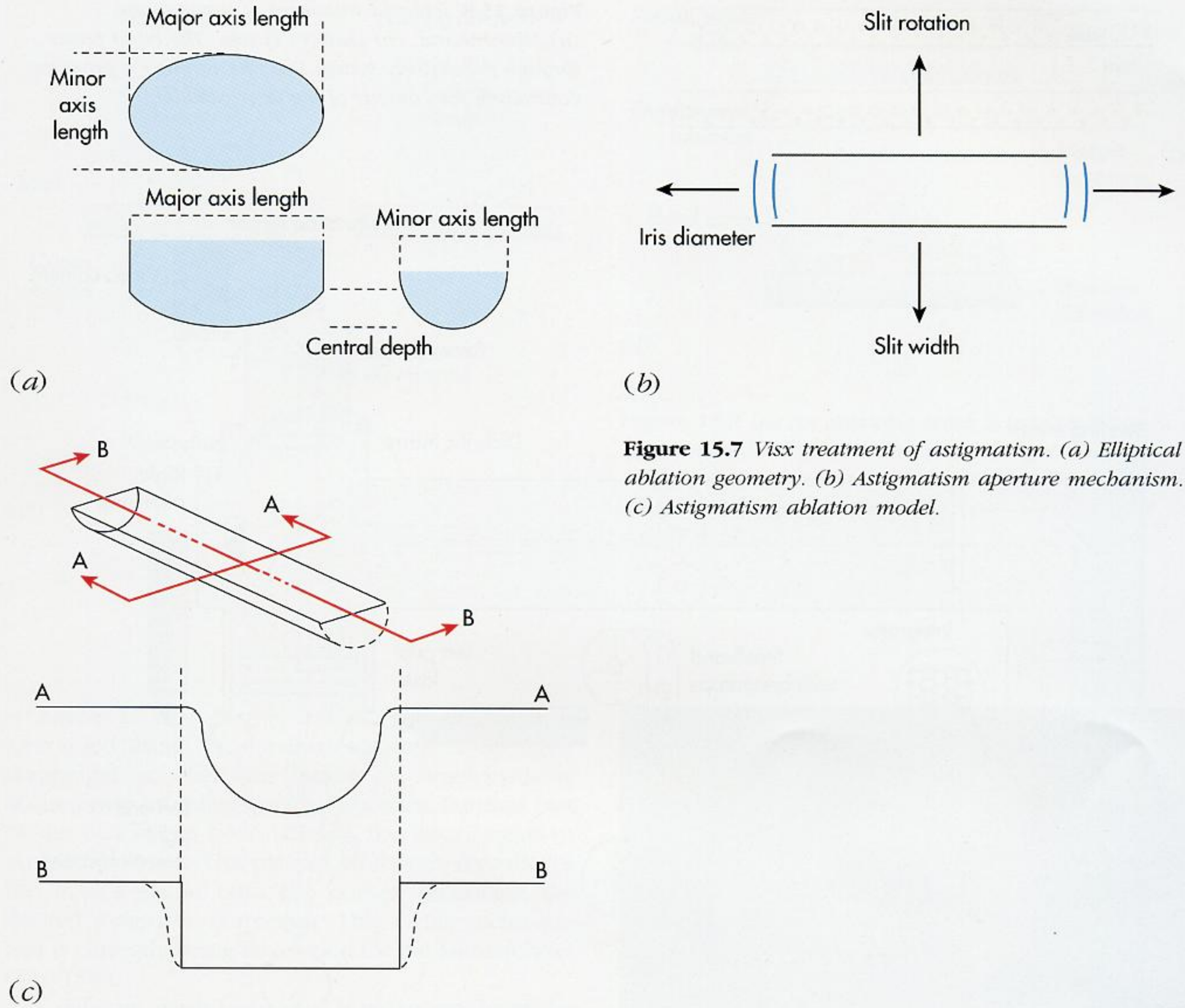

Figure 15.7 *Visx treatment of astigmatism. (a) Elliptical ablation geometry. (b) Astigmatism aperture mechanism. (c) Astigmatism ablation model.*

astigmatism was published in early 1991.[12] The techniques and computer programs for PRK to create a radially symmetric ablation with a greater depth centrally than peripherally in order to correct myopia were already well established. In general terms, utilizing incisional or laser techniques, one can correct corneal astigmatism by selective flattening of a steep meridian or steepening of a flat meridian. Munnerlyn and his associates modified the laser software to have a large diameter laser beam pass through an aperture created by a mobile set of parallel blades that the computer controls.[12] The width of the slit changes with the separation or narrowing of the blades in order to provide a controlled cylindrical ablation; the slower the blade movements for a constant pulse rate, the greater the astigmatic correction (Fig. 15.7). The cornea is relatively flattened in the meridian perpendicular to the long axis of the slit. This long axis is called the 'mechanical axis' and would ideally undergo no refractive change if only astigmatism were to be corrected. Initially the astigmatic correction was performed as a cylindrical ablation followed by a second, spherical, ablation to correct the residual myopia. This method has been termed the 'sequential' method of ablation, referring to performing the treatments for myopia and astigmatism in two phases.

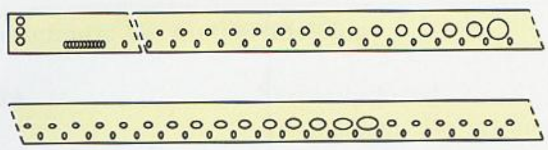

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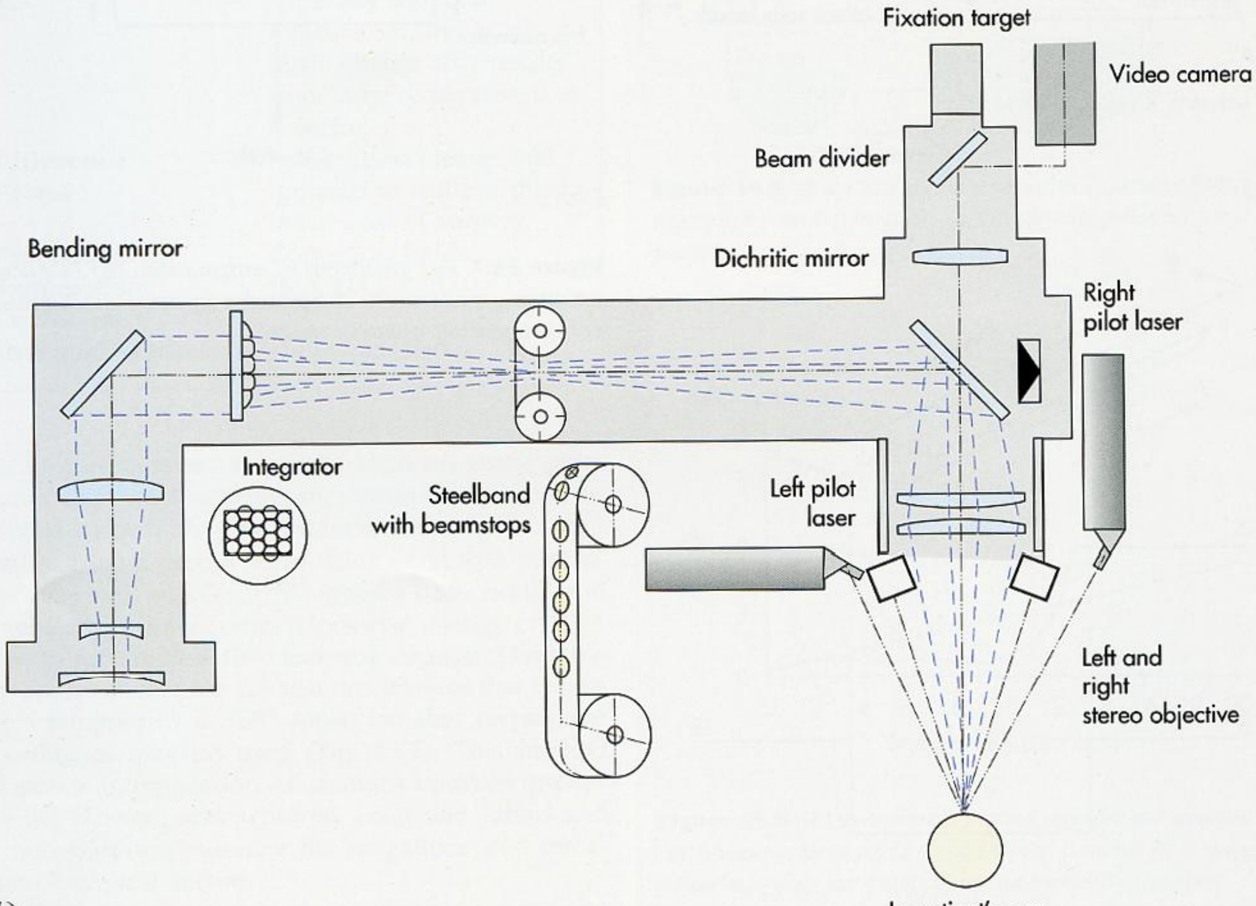
Figure 15.8 *Schwind treatment of astigmatism. (a) Maskenband. (b) Delivery system. The band passes through the delivery system like film through a projector controlling the contour of the laser ablation.*



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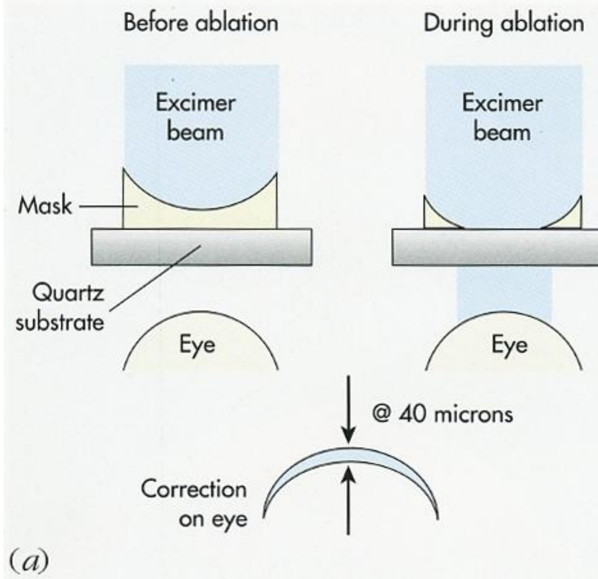
The Visx software was further modified to combine expansion of the inner parallel blades with a controlled contraction of a round diaphragm.[12] This allowed the full myopic and astigmatic correction to be sculpted into the cornea in one, smooth ablation. This technique has been termed the 'elliptical' method. The elliptical program effectively avoids excessive narrowing of the minor axis of the ellipse, as the surgeon is precluded from treating astigmatism in excess of the amount of spherical myopia.

The Schwind excimer laser controls its beam profile by means of a series of apertures on a revolving band that pass between the laser and the eye, much like film running through a movie projector (Fig. 15.8). Round apertures are employed to guide their purely myopic ablations, and an oval or slit aperture aligned at the appropriate axis to treat astigmatic errors.[13]

Another approach that allows the excimer laser to correct astigmatism is to use an erodible mask to control the shape transfer.[14] A polymethylmethacrylate button, of a specific shape determined by the refractive error of the patient, is placed between the beam and the cornea. The ablation rate of the button



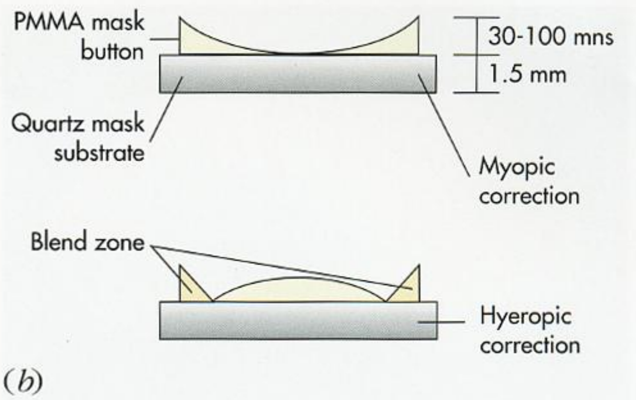


Figure 15.9 *(a) An ablatable mask is inserted between the laser and the eye. (b) The mask transfers the preset astigmatic contours onto the cornea. This is the technique being used by the Summit laser.*

is similar to that of the cornea. The treatment is performed using the maximal aperture of the laser diaphragm so that the button is simultaneously ablated over its entire surface. When the thinnest part of the button has been ablated, the laser begins to sculpt the cornea. This process effectively reproduces the mask's shape onto the cornea producing the desired astigmatic correction. This is the technique that is currently being developed for the Summit laser (Fig. 15.9).

A different mask technique is being employed by the Aesculap–Meditech MEL 60 excimer laser. Dausch and his associates developed a rotating mask with an hourglass-shaped opening over a slit delivery system that uses a scanning process rather than a broad beam exposure (Fig. 15.10).[15] If the mask is rotated in equidistant angular steps over 360°, a symmetric ablation is achieved. However, if the mask is held in one position longer than another, the ablation depth will be increased in a desired meridian. Thus, by selectively allowing more time in a specific meridian during the rotation, astigmatism can be corrected. By altering the mask aperture Dausch and co-workers are able to treat hyperopic astigmatism.[15] For mixed astigmatism they used the same technique in a two-stage process, correcting first the myopic cylinder followed by a spherical hyperopic correction, or by correcting first the hyperopic cylinder and then the residual myopia (Fig. 15.11).

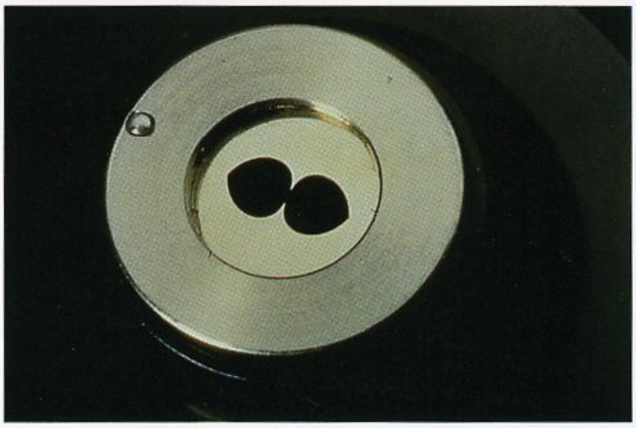
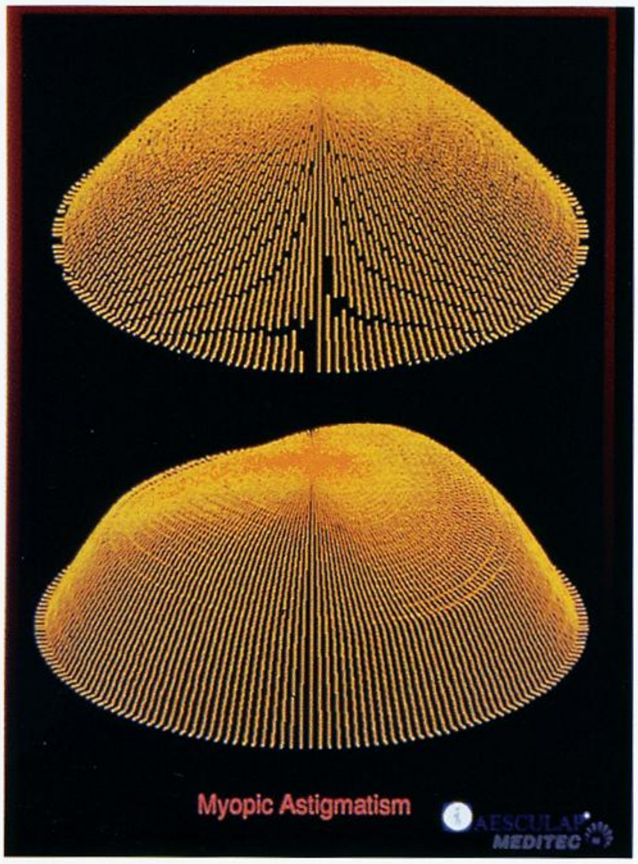


Figure 15.10 *Meditech treatment of astigmatism utilizes a rotating mask. By controlling the time the mask spends in different alignments during the rotation, an ablation can be performed to treat both myopic and hyperopic astigmatism.*

The Technolas (Fig. 15.12), Nidek (Fig. 15.13) and Lasersight lasers all employ a scanning mechanism to correct astigmatic errors. The Technolas model has the laser beam move along the axes of astigmatism with an increasing diameter. The Lasersight and



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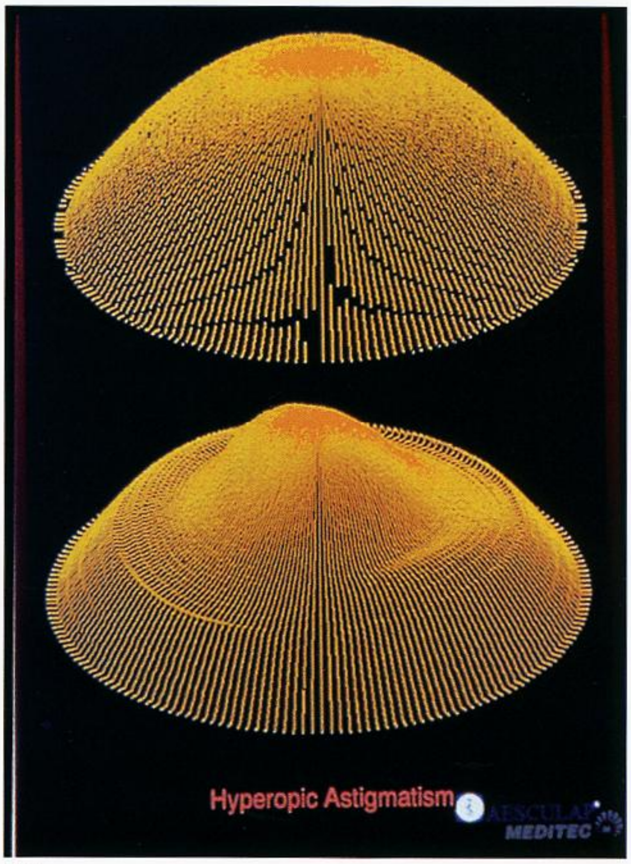

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Figure 15.11 *(a) Schematic contour map of a cornea after a Meditech laser ablation for myopic astigmatism. (b) Schematic contour map of a cornea after a Meditech laser ablation for hyperopic astigmatism.*

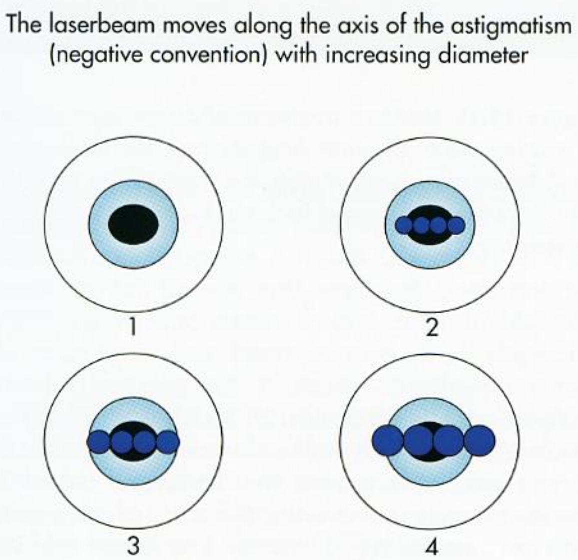

Figure 15.12 *The Chiron Technolas scanning mechanism alters the diameter of the laser beam as it moves along the axes of astigmatism to carve an astigmatic ablation.*

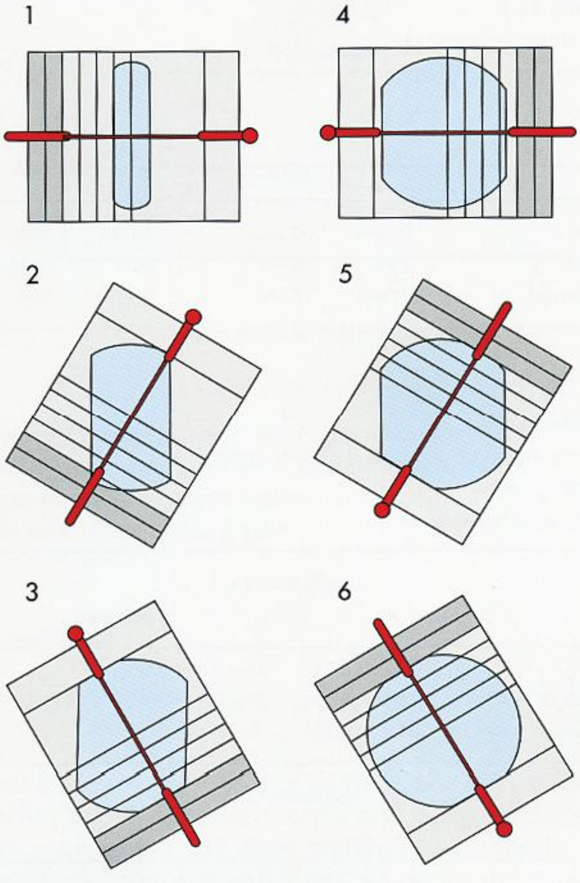

Figure 15.13 *The Nidek laser uses a scan and rotate model to create astigmatic changes in the corneal topography.*

Nidek lasers utilize a similar concept in their rotating scanning beam. Recent innovations by Technolas and Lasersight have introduced the technique of a flying spot facilitating treatment of hyperopic astigmatism by selective ablation for steepening at the flat axis.

Astigmatic keratotomy, which uses a knife to create a partial thickness cut in the cornea on the steepest axis, has been used to combat astigmatism since 1885 when Schiotz described a penetrating limbal incision in a post-cataract patient with high astigmatism.[16] Fyodorov[17] popularized modern anterior corneal keratotomy techniques that have been refined over the past 25 years. Agapitos and Lindstrom recently reported on the state of arcuate keratotomy and found the results to be only 'reasonable' and often 'unpredictable'.[18] There is no published vector analysis of results of astigmatic keratotomy and thus quantitative comparison with PARK is not possible. Despite the unpredictability of the results, Lipschitz et al[19] and Ring et al[20] have both advocated a two-step procedure combining both incisional and laser surgery. To treat compound myopic astigmatism these authors first use an incisional astigmatic keratotomy that is followed by a spherical photorefractive keratectomy.

All of the above methods are used to treat regular astigmatism. The initial surgical plans to correct astigmatism with the excimer laser were based on the refractive astigmatic error converted to the corneal plane as the sole determinant of treatment. By the early 1990s, advances in corneal topographic mapping gave new parameters to guide the corneal refractive surgeon, but the quantitative information provided has not been fully utilized. We advocate the consideration of corneal topography when developing the surgical plan to treat regular astigmatism to reduce the amount of resultant corneal astigmatism and to optimize its meridian.[4,38]

Astigmatism that is not regular cannot be treated by the application of any simple geometric pattern of tissue removal. However, with computerized topography, the surgeon can identify high, steep areas of the cornea. These areas then can be selectively ablated with small, circular focal treatments, as would be done for a phototherapeutic keratectomy (PTK).[21] This can be followed by a PRK centered over the entrance pupil. The overall effect minimizes the differences between steeper and flatter areas on the topographical map, reduces the irregular astigmatism and improves the optical quality of the cornea.

RESULTS: THE EFFECTIVENESS OF THE EXCIMER LASER IN CORRECTING ASTIGMATISM

MYOPIC ASTIGMATISM

The first clinical report of the excimer laser creating toric ablations to treat cylindrical errors was published by McDonnell and colleagues in 1991.[22] Four patients with compound myopic astigmatism were successfully treated. An average of 83% ±17% of the refractive astigmatism was corrected. These initial good results led many surgeons around the world to start treating myopic astigmatism with the excimer laser.

In Melbourne there are now data on 343 patients who have had more than a 1 year follow-up after excimer laser correction of myopic astigmatism.[23] Myopic astigmatism was treated by using either the sequential or elliptical method. In the sequential method, the amount of minus sphere to be treated is calculated by first determining the expected hyperopic shift. This is calculated by subtracting 1.00 D from the amount of cylinder and then halving the remaining amount of cylinder to provide a spherical equivalent.[24] This amount of expected hyperopic shift is then subtracted from the spherical component to give the residual spectacle myopia to be treated. With the elliptical method, no correction for hyperopic shift is required.

The PARK procedures were divided into single or multiple treatment zone sizes according to the amount of correction. For corrections of −5.00 D or less spherical equivalent (SE) (low myopia), we used a single 6.0 mm zone; for corrections > −5.00 D SE and ≤ to −10.00 D SE (high myopia), we used two zones (5.0 mm and 6.0 mm); for corrections > −10.00 D (extreme myopia), we used three zones (4.5 mm, 5.0 mm and 6.0 mm).[23] The myopic correction was divided equally into each zone. When an elliptical astigmatic correction was performed, the cylindrical correction, which did not exceed 80% of the spherical dioptric correction for the zone, was entered into the largest (6.0 mm) zone size. When the cylinder exceeded 80% of the sphere to be treated in the 6.0 mm zone, the astigmatic correction was shared equally between the 5.0 mm and 6.0 mm zones in order to prevent overlapping boundaries and create concentric ellipses and evenly contoured ablation zones. No astigmatism was corrected in the 4.5 mm zone when this zone was employed for the correction of > −10.0 D spherical equivalent.

Our results indicate that both the myopic (Table 15.1) and the astigmatic components of myopic astigmatism can be effectively treated with the excimer laser (Table 15.2). Postoperatively, 68% of the patients had a spherical equivalent within 1.00 D of plano and 77% within 2.00 D of plano at 6 months.[23] If one looks only at patients whose preoperative refraction was −10.00 D or less the results improve to 73% within 1.00 D and 87% within 2.00 D. Seventy-two per cent of these patients had an uncorrected visual acuity equal to or better than 20/40.

Vector analysis was used to assess the change in both topographic and refractive astigmatism. When comparing the targeted change in astigmatism with both the elliptical and sequential methods for the treatments prior to April 1993, the SIA, both by refraction and topography, showed an undercorrection. Therefore, a calculated adjustment of 1.2 was factored into all our subsequent astigmatic treatments. This adjustment has now been incorporated into the Visx software and has led to less undercorrection with the SIA closer to the TIA (Fig. 15.14) and a correction index closer to 1.0.

When measuring the success of the procedure at 12 months, the index improved from 0.55 to 0.43, which means that nearly 60% correction of the astigmatism is being achieved. When this is stratified into three groups of spherical myopia, 0–5 D, 5–10 D and 10–15 D, the index of success by refraction shows that there were fairly equivalent results between the groups. However, the visual outcome was worse for the extreme myopes.[25]

Although the magnitude of correction remained excellent, results in Melbourne for extreme myopes showed a less successful visual result than for low or high myopes. We have 1 year follow up on 58 extreme myopes who have had PARK. We had a post-treatment mean spherical equivalent of −1.91 D

Table 15.1

Accuracy of refraction

	12 Months			
	PRK		*PARK*	
	±1D	*±2D*	*±1D*	*±2D*
Low	90.6%	99.1%	84.9%	98.8%
High	75%	95.5%	62%	88.3%
Extreme	77.8%	77.8%	28.2%	50%

Table 15.2

Mean correction index × 100 (per cent)

Alpins' method

95% confidence limits

Coefficient 1.0			
Elliptical		*Sequential*	
Low (n = 52)	77 (66, 91)	Low (n = 22)	71 (58, 86)
High (n = 63)	78 (64, 97)	High (n = 9)	74 (59, 93)
Extreme (n = 13)	104 (60, 189)	Extreme	–
Coefficient 1.2			
Elliptical		*Sequential*	
Low (n = 70)	101 (88, 115)	Low (n = 16)	82 (59, 96)
High (n = 66)	86 (79, 99)	High (n = 1)	69
Extreme (n = 18)	74 (35, 153)	Extreme	–

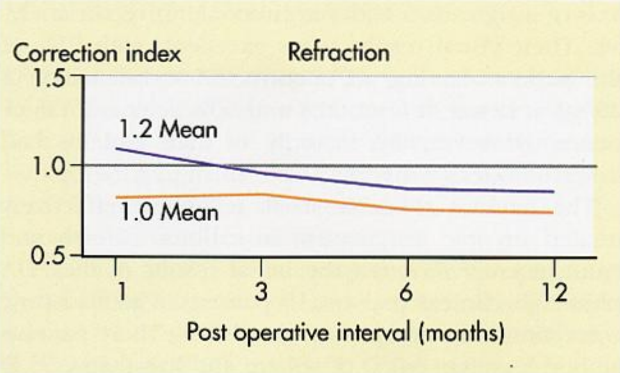

Figure 15.14 *Correction index, showing SIA/TIA for PARK before and after the 1.2 adjustment with the Visx laser as measured by refraction at the corneal plane. We are now closer to our goal.*[40]

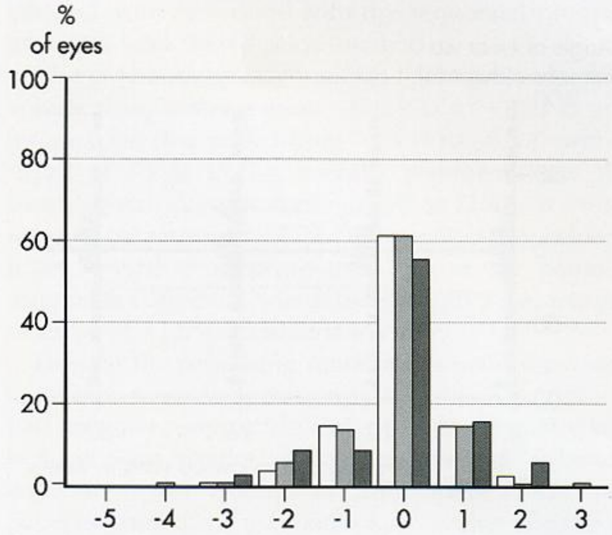

Figure 15.15 *Graph showing the loss and gain in best corrected visual acuity for 333 PARK patients.*[40]

and a mean astigmatism of –1.06 D ±0.97. Refraction within 1.00 D of emmetropia was achieved in 39% of the patients and 56% were within 2.00 D. The mean angle of error was –6.16° ±17.3°. Retreatment was required in 30% of the patients. The mean haze score remained 1.0 at one year, and 15% of the eyes lost one line of best corrected acuity, with 8% losing two or more lines (Fig. 15.15).

There was also a difference in the undercorrection between the patients treated with an elliptical ablation, and sequential treatments of a plano-cylindrical treatment followed by a spherical treatment. The SIA is closer to the TIA for the elliptical treatments (Fig. 15.16). However, the sequential method was used for more difficult patients, where the amount of cylinder was larger relative to the spherical error.

Our magnitude of correction has become satisfactory. However, our overall index of success was only 0.43. This can be explained by the angle of error. Although the mean angle of error measured by both refraction and topography is near zero, the standard deviation is 30° wide. This can be confirmed on scatter plots (Fig. 15.17) which show a wide distribution from –90° to +90° with the greatest variation being with low levels of attempted astigmatic correction. The subjective test of refraction shows a predictable peak at the zero axis. There is a potential for future improvement in astigmatism surgery by improving the accuracy in the axis of applied treatment. This is achievable by better identification of the steepest corneal axis at the time of surgery, more accurate laser beam alignment, and ensuring completeness of epithelial removal.

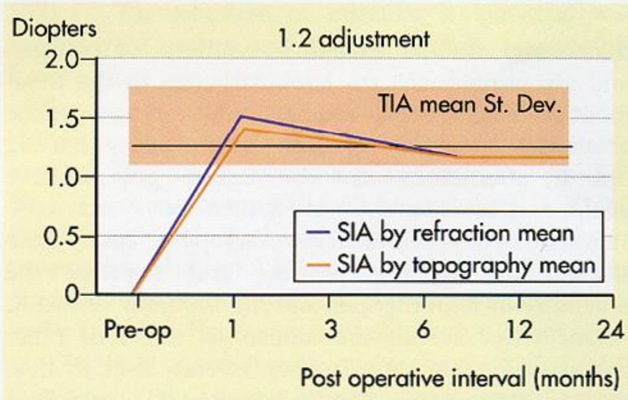

Figure 15.16 *SIA compared to TIA by both refraction and topography after the Visx 1.2 systematic adjustment.*[40]

Other important factors in unwanted astigmatic change are the irregularity of epithelial healing and

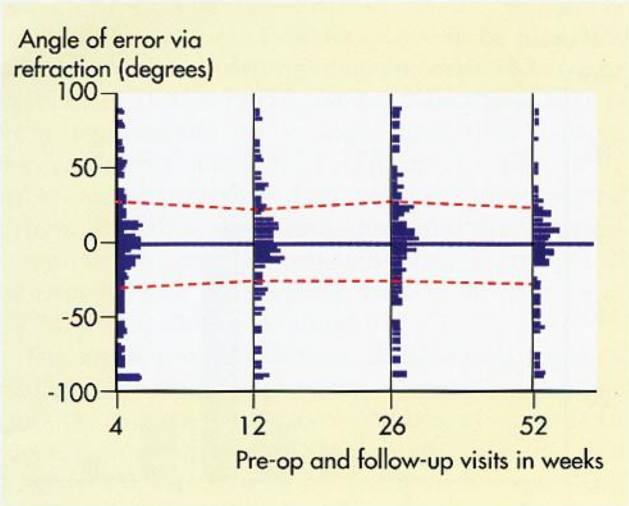

Figure 15.17 *Angle of error of treatment. The mean axis misalignment is close to zero and constant over time. However, the scatter is wide with a wide standard deviation band.*

thickening and the excessive synthesis of collagen and glycosaminoglycans by keratocytes in the treatment zone. These may lead to a thickening over the ablation zone and irregular topography causing optical aberrations and decreased postoperative vision.[26] Developments in antimitotic[27] and non-steroidal anti-inflammatory therapy[28] may help smooth the healing process and improve the outcome for high myopes and the accuracy of PARK.

Our visual results are similar to those of other groups using the Visx Twenty/Twenty laser to treat myopic astigmatism. Pender reported 1 year follow up on six patients who were treated for low or moderate myopia and astigmatism.[29] All had uncorrected visual acuities of 20/50 or better, and 62.5% had better than 20/40 vision. Two patients lost one line of best corrected vision and in six of the eight eyes they noted a change in axis postoperatively of greater than 5° from the preoperative cylinder.

Kim et al in Korea reported on 168 eyes that had treatment for myopic astigmatism with the Visx system.[30] Their mean preoperative astigmatism was 1.51 D. Their results showed, by simple analysis, a decrease in astigmatism of 56%. By comparing the preoperative and postoperative refractive astigmatism axis, they found that the axis of astigmatism changed > 10° in 54% of the eyes. However, there is limited value in simply comparing pre- and postoperative axis of astigmatism without undertaking vector analysis. Their visual results were excellent, with 91% of the patients having an uncorrected visual acuity of 20/40 or better at 6 months and 60% seeing 20/25 or better. However, the majority of their patients had low to moderate myopia.

The Summit ablatable mask technique effectively treated myopic astigmatism in rabbits.[31] Hersh and Patel recently reported the initial results of the FDA phase 2b clinical trial on 10 patients who had toric corrections for myopic astigmatism.[32] Their patients all had less than 6.0 D of sphere and less than 2.75 D of astigmatism. The mean astigmatism decreased from 1.48 D preoperatively to 0.86 D postoperatively, with 63% achieving an uncorrected visual acuity of 20/40 or better. Their follow up was only for 2–4 months and vector analysis was not performed. Cherry et al also reported 3 month data on 34 eyes who were treated with the Summit ablatable mask for myopic astigmatism.[33] They found a reduction of approximately 50% in refractive astigmatism. Significantly, the objective changes of keratometry were reported to show less change than the subjective values of refraction. Again, the lack of vector analysis means it is not possible to assess the efficacy of the Summit lasers in treating astigmatism.

Dausch et al report 3-month results with the Meditech MEL 60 laser. They treated 29 patients with myopic astigmatism.[15] The mean preoperative cylindrical refraction was –2.10 D with a range from –1.0 D to –5.0 D. Postoperatively the mean astigmatism was reduced to –0.10 D with a range from 0 to –2.25 D. They also report a mean shift in axis of 2.0°, with a maximum change of 19°. The uncorrected visual acuity improved from a mean of 20/180 to 20/25 after laser surgery. However, 15% of these patients lost one line of best corrected acuity and 3% lost two Snellen lines, while 12% gained one line of best corrected vision. Again, vector analysis was not provided, making comparison with other systems difficult.

An initial report of 27 eyes that underwent PARK with the Coherent–Schwind Keratom gives promising visual results.[34] Eighty-two per cent of the eyes had an uncorrected visual acuity of 20/40 or better with 46% seeing 20/25. However, 40% of their patients were overcorrected by 1.0 D or more and 9% of their patients lost two or more lines of Snellen best corrected acuity. No mention of the vector changes in astigmatism or amount of refractive astigmatism was made.

As of June 1996, we are not aware of published data for the Technolas, Lasersight, and Nidek scanning laser treatment of astigmatism.

HYPEROPIC ASTIGMATISM

Dausch and Klein treated 23 patients with stable hyperopia of less than +8.00 D with stable astigmatism of less than –6.50 D.[15] Thirteen patients had hyperopic astigmatism and 10 had mixed astigmatism. They used the Meditech laser, and aimed for emmetropia in all cases.

For their group with compound hyperopic astigmatism, the mean preoperative spherical equivalent was +4.00 D ±1.28 D. After three months this value averaged –0.88 D ±1.73 D. The mean cylinder changed from –2.70 D ±1.23 D preoperatively to –0.40D ±0.13 D at 3 months. They reported that the postoperative refractive axis of astigmatism was within 10° of the preoperative axis in all eyes. Best corrected vision remained the same with three eyes gaining one Snellen line of best spectacle correction and three eyes losing one line of best acuity. The mean uncorrected acuity improved from 20/150 preoperatively to 20/50 at 3 months, with 61.5% obtaining an uncorrected acuity of 20/40 or better. However, two partially sighted eyes did not have the potential of 20/40 vision.

Their patients with mixed astigmatism were treated first with a myopic cylindrical ablation followed by a hyperopic spherical correction. They treated 10 eyes with an average preoperative spherical equivalent of + 0.47 D ±1.08 D and a mean preoperative cylinder of –5.02 D ±0.77 D. Three months after treatment the mean spherical equivalent was –0.22 D ±0.96 D and the mean cylindrical refraction was –0.25 D ±0.60 D. Seven of the 10 patients had an uncorrected visual acuity of 20/40 or better and two eyes did not have 20/40 potential.

The technique used for hyperopic astigmatism leaves the central cornea, including Bowman's layer, intact. Thus haze across the visual axis is less likely. Despite the small number of patients treated and the short follow up period, these results are encouraging.

POSTSURGICAL ASTIGMATISM

We used the Visx laser to treat patients with astigmatism remaining as the result of surgical procedures.[35] There is now 6-month data on 51 eyes in this group. Sixteen of these patients were post-penetrating keratoplasty, 14 had astigmatism induced from cataract surgery, nine were treated for post-radial keratotomy, three had corneal scars, and three were treated for astigmatism induced by glaucoma or retinal procedures. The treatment technique was divided, with 58% done with the sequential program and 42% with the elliptical method.

The post-keratoplasty patients had a wide range of spherical equivalents from –19.25 D to +2.50 D and astigmatism that varied from –1.5 D to –8.0 D with a mean of –5.02 D. Six months postoperatively the mean spherical equivalent was +0.10 D ±2.71 with a mean astigmatism of –3.04 D. Overall, the correction index was 0.73 showing that 73% of the planned astigmatic correction was achieved with a mean angle of error of +12.5° (counterclockwise).

Despite the promising numerical results, the visual outcomes were disappointing. Many of these patients had irregular astigmatism that decreased visual acuity beyond what would be expected from the spherical equivalent and amount of astigmatism. Only two patients gained an unaided visual acuity of 6/12 or better. Seven had an acuity worse than 6/18 and four remained worse than 6/60. The mean grading of corneal haze was 1.08, with 15% having grade 2+. Three patients went on to have a failed graft from irreversible rejection, four were retreated with the excimer laser and two had astigmatic keratotomy performed. Four became hyperopic by more than 1.00 D. The problem of irregular astigmatism was ineffectively treated and may be partially responsible for the poor visual results.

The post-cataract patients fared slightly better. However, they also had less myopia and less astigmatism. The mean spherical equivalent was –2.75 D ±2.27, with a mean astigmatism of –3.86 D ±1.22. Postoperatively, 43% had an unaided visual acuity of better than 6/12, and 92% were within 2.00 D of the planned refraction with a mean astigmatism of –1.56 D ±1.08. Haze was minimal, with a mean score of 0.46. Half of the patients were greater than 1.00 D hyperopic. The mean postoperative spherical equivalent was +1.36 D ±1.96.

The patients who were treated for astigmatism resulting from radial keratotomy had results which approached that of primary PARK. They also had less myopia and astigmatism to correct. The group had a mean spherical equivalent of –3.75 D ±2.18, with a mean astigmatism of –1.72 D ±1.66. Postoperatively all had an unaided acuity of better than 6/18, with one-third seeing 6/6 or better. One patient required retreatment and none developed severe haze.

IRREGULAR ASTIGMATISM

Gibralter and Trokel reported two patients with postoperative irregular myopic astigmatism.[21] They identified steep areas by corneal topography, and performed phototherapeutic ablations in overlapping confluent 4.0 mm zones at depths of 10 or 20 microns, centered over the localized steep areas. This was followed by a spherical correction with a 6.0 mm zone. They obtained a change of 4.00 D of localized refractive change with a 20 micron ablation of 4 mm in diameter.

These initial results suggest that the excimer laser can be used to treat irregular astigmatism, although currently this is a rather crude technique. Improvements in topographical analysis of the corneal surface will allow more accurate predictions of the size and depth of the areas to be ablated. In the future we can expect that the excimer laser will be able to convert an irregular central corneal surface into a predetermined regular and symmetric curved surface employing asymmetrical ablation patterns.[36] This holds promise for patients with irregular central corneal astigmatism of an idiopathic type, but also after trauma, scarring, pterygia excision, penetrating keratoplasty, or other surgical procedures.

The introduction of corneal topography data into the surgical plan raises new complexities concerning the optimal treatment of astigmatism. These issues include optimizing corneal shape and astigmatic orientation,[38,39] and the potential application of topographical mapping to guide asymmetrical ablations.[36] Alignment of treatment and corneal axis is likely to be improved by the ability to view a real-time topographical image through the surgical microscope at the time of surgery. The quantitative data provided by computer-assisted videokeratography are likely to play an increasing role in the objective assessment of astigmatism surgery.[40]

Irregularities of corneal epithelial healing are currently difficult to control or predict and can create their own axes of irregular astigmatism. As our topographical analysis improves, our ability to modulate corneal healing expands, and new laser technologies are developed, we will be better able to create the exact astigmatic results we desire.

CONCLUSION AND FUTURE DIRECTIONS

There has been significant success in correcting astigmatism with the excimer laser. The benefits provided by vector analysis of outcomes enable the results of astigmatic treatment to be separated from those of the concurrent spherical changes induced by surgery.[37] Planning astigmatism surgery, with the assistance of vector planning,[38] helps the surgeon approach a complex subject, and may provide the direction necessary to improve the capabilities of excimer laser machines and enhance the visual results of surgery.

EXCIMER LASER TREATMENT OF ASTIGMATISM – KEY POINTS

- Vector analysis is essential in evaluating astigmatic changes.
- The excimer laser is effective in carving astigmatic ablations on the cornea.
- Visual results after PARK are similar to those of PRK.
- Irregular epithelial healing after any excimer ablation induces a random, inadvertent astigmatic change that affects the outcome of PARK, particularly when treating small amounts of astigmatism.

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