Role of Hemidivisional Corneal Topographic Astigmatisms (CorTs) in the Regularization and Reduction of Irregular Astigmatism

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Purpose: To demonstrate how the concept of hemidivisional corneal topographic astigmatism (hemiCorT) enables the planning of hemidivisional corneal treatments to reduce irregularity and overall astigmatism.

Methods: Whole-of-cornea corneal topographic astigmatism (CorT) is calculated from topography data derived from a corneal topographer or tomographer. The cornea is conceptually divided into 2 hemidivisions along the flat meridian of the CorT. For each hemidivision, hemiCorTs are calculated. The regularization treatment for each hemidivision is the treatment required to target the whole-of-cornea CorT, which is a symmetrical orthogonal corneal astigmatism. The regularization is then combined with astigmatism reduction treatment, which could be a conventional refractive treatment or a vector-planned treatment. For each hemidivision, the combined astigmatic effect of the regularization treatment and reduction treatment can be determined through double-angle vector summation. The 2 hemidivisional treatments together regularize and reduce corneal astigmatism.

Results: A theoretical pair of hemidivisional treatments is derived from an actual example of a cornea displaying idiopathic asymmetric nonorthogonal astigmatism.

Conclusions: HemiCorTs allow for the design of hemidivisional corneal treatments of asymmetric nonorthogonal astigmatism. Such treatments should be suitable in the routine treatment of commonly occurring irregular astigmatism, while also allowing the spherical refractive error to be treated concurrently.

Key Words: irregular astigmatism, corneal topographic astigmatism (CorT), regularization

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In 1998, Alpins[1] introduced a method for regularizing a global form of irregular astigmatism characterized by corneal asymmetry. This type of asymmetry is most easily visualized as an asymmetric bowtie pattern on a corneal axial power map, where the 2 halves of the bowtie pattern may differ in both extent and orientation. It was assumed that the cornea could be divided into a superior and inferior hemidivision, and that each corneal hemidivision could be characterized by a separate measure of astigmatism. However, at that time, it was not clear how to acquire such hemidivisional measures of astigmatism.

In this article, we show how corneal topographic astigmatism (CorT) and its corresponding hemidivisional analogues (hemiCorTs)[2] are well suited to be used as the basis for a combined astigmatic regularization and reduction treatment. The CorT is a measure of corneal astigmatism that closely corresponds to manifest refractive cylinder, even after the effect of the Javal rule has been removed. The hemiCorT is a generalization of the CorT that provides a more localized estimate of corneal astigmatism contributed by one corneal hemidivision.

One important property of the 2 hemiCorTs is that their vector sum will be equal to the CorT if no measurement data are missing. This property of the hemiCorTs means that it is possible to design a treatment that regularizes corneal astigmatism without changing the overall astigmatism of the whole cornea as characterized by the CorT. Such a regularization treatment has the advantage that it allows for a concurrent treatment of regular astigmatism using existing nomograms, instead of requiring a subsequent treatment of regular astigmatism after a substantial healing period. We provide an example of how to combine a regularization treatment with a concurrent reduction of astigmatism in a single treatment.

The method that we describe is intended to be used as part of an excimer laser ablation strategy, although it has been partly motivated by early attempts to perform asymmetric astigmatic keratotomy.[3] To allow comparison with other ablative methodologies for treating irregular astigmatism, we analyze the effect of the regularization treatment on higher-order Zernike coefficients.

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MATERIALS AND METHODS

In this section, we start out by introducing the concepts of the CorT and the hemiCorT. Then, we describe the regularization procedure used in this article, and consider how regularization can be combined with astigmatism reduction in a single procedure.

CorT

The CorT is a measure of corneal astigmatism that was designed to correspond closely to the manifest refractive cylinder. The CorT can be thought of as the best-fit optical cylinder for an annular region of the cornea with a correction for missing data, centered on the visual axis. The inner and outer radii of the annular region are dependent on the type of measurement and the type of topographer or tomographer being used. The CorT has been previously calculated on the basis of both axial curvature measurements[2] and total corneal power measurements.[4] The mathematical details of the CorT are summarized in Supplemental Digital Content 1 (http://links.lww.com/ICO/A599).

To compare the CorT with other measures of corneal astigmatism, the standard deviation of the magnitude of ocular residual astigmatism (ORAsd)[2,5] was calculated for each measure. The ORAsd is a quantitative descriptor of the variability in the vector difference between the measure of corneal astigmatism used and the manifest refractive cylinder. The lower the ORAsd, the better the correlation between the measure of corneal astigmatism and manifest refractive cylinder. Based on the magnitudes of the ORAsds, the CorT based on anterior axial curvature has been shown to outperform manual keratometry, simulated keratometry, and paraxial curvature matching.[2] Also, the CorT based on total corneal power has been shown to outperform the CorT based on anterior axial curvature.[4]

The ORAsd automatically accounts for any systematic non-zero difference between corneal astigmatism and refractive cylinder because it measures the variability around the mean magnitude of ocular residual astigmatism (ORAmean). The Grosvenor modification of the Javal rule[6–9] states that the refractive cylinder is roughly equal to keratometric astigmatism plus a systematic difference of 0.50 D against-the-rule. The important part of this linear relationship is that the gradient is unity, which means that once the systematic difference has been subtracted out, the refractive cylinder and keratometric astigmatism can be compared directly for equality.

HemiCorT

The hemiCorT is basically the same as the concept of the CorT, but calculated on the basis of only one hemidivision of the cornea,[2] as if the other hemidivision were the first hemidivision rotated by 180 degrees about the visual axis. The hemiCorT is useful as a quantitative description of the distribution of corneal power over the corneal hemidivision. Mathematically, it turns out that if there are no missing measurement data, the summated vector mean of the 2 hemiCorTs of a cornea are guaranteed to equal the CorT (mathematical explanation in Supplemental Digital Content 2, http://links.lww.com/ICO/A600).

In this article, the cornea will be divided into hemidivisions along the flat meridian of the CorT, as suggested in the original definition of the hemiCorT.[2] Because the CorT is calculated using a large annular region of the whole cornea (see previous section), the flat meridian of the CorT may not directly correspond to the local flat meridia in each corneal hemidivision, nor be at right angles to the local steep meridia represented by the topographic bowtie patterns.

Regularization

The regularization procedure used in this paper is designed to leave the overall corneal astigmatism unchanged. Each corneal hemidivision is treated with an astigmatic treatment restricted to that hemidivision, which changes the hemiCorT to the CorT. In the case in which there are no missing measurement data, the treatments to the 2 corneal hemidivisions turn out to be equal in magnitude but perpendicular (mathematical explanation in Supplemental Digital Content 2, http://links.lww.com/ICO/A600), which means that their effects to astigmatism of the entire cornea should cancel out exactly, thus causing no net effect on the refractive cylinder.

For the 2 hemidivisional treatments to cancel out exactly, the visual effect of each of the treatments must be equal in magnitude. This is achieved by calculating the CorT centered on the visual axis, and having the dividing line of the corneal hemidivisions pass through the visual axis.

The regularization procedure as described is a specific case of the general regularization procedure previously described by Alpins,[1] constrained to leave the amount of corneal astigmatism and refractive cylinder unchanged. This constraint is important when regularization is combined with astigmatism reduction, as described in the next section.

Combination of Regularization and Reduction

The problem with a pure regularization treatment is that it is likely to improve the visual acuity and quality of vision,[10,11] but it leaves any manifest refractive sphere and cylinder untreated. Previously, topography-driven regularization treatments have been combined with refractive treatments, but this necessitates the estimation of the change of refractive sphere and cylinder due to the regularization treatment.[12,13] Ideally, a regularization treatment would be combined with a standard refractive treatment or a vector planning treatment to reduce astigmatism without a need to adjust the nomograms used, so that the surgeon can still expect an excellent refractive result. The pure regularization treatment described above does not change the overall corneal astigmatism and can be implemented to leave the mean corneal curvature unchanged. This makes it simple to combine it with a treatment of refractive astigmatism without requiring any adjustment of the refractive treatment nomogram.

Notation

In the results section, we use 3 distinct types of notation, as dictated by both clarity[14] and definition.[15]

1. Manifest refraction data are given in the spherocylindrical (or cylindrical) form using positive cylinders, so −1.00/+2.25 × 115 degrees means −1.00 D sphere and +2.25 cylinder with the axis at 115 degrees.
2. Corneal astigmatisms (including CorTs and hemiCorTs) and changes to corneal astigmatisms (including flattening effects) are shown using magnitude and meridian, for example, astigmatism of 1.90 D with a steep meridian at 102 degrees; or 1.55 D of flattening at 158 degrees.
3. Target-induced astigmatisms (TIAs),[15] which are Alpins vectors, are shown using the magnitude and Alpins axis, for example, 1.55 D Ax 68 degrees. Note that the magnitude here must always be positive, which means that the Alpins axis of a TIA can be interpreted as the direction of the equivalent steepening force.

RESULTS

In this section, we show a fully worked example of how to apply the methodology described above. The astigmatic reduction treatment shown here is based on vector planning because this is the general case; a pure refractive astigmatic reduction treatment can be treated as a special case of vector planning with 100% emphasis on treating refractively. In the example below, we use an emphasis of 60% refractive, 40% corneal, which has been shown empirically to give good results.[16–18]

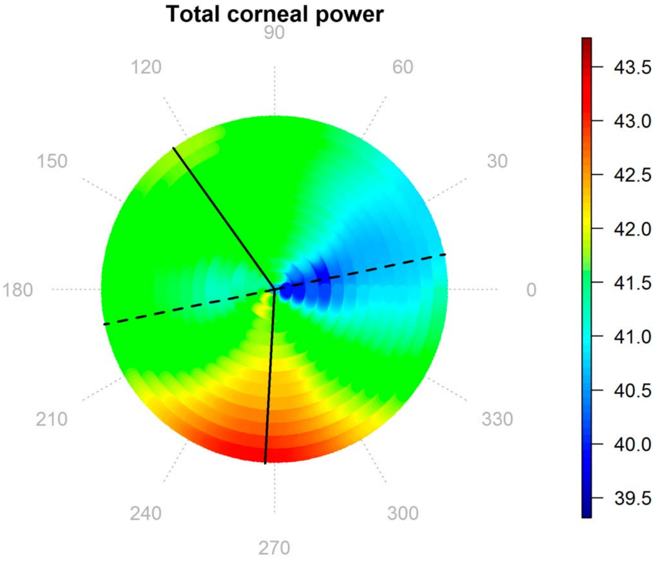

FIGURE 1. Total corneal power map. The map shows the data for the innermost 13 rings, up to a diameter of 5.2 mm. The dashed line is the flat meridian of the CorT, which is at 12 degrees. This dashed line divides the cornea into 2 hemidivisions. The solid lines show the steep meridia of the hemidivisional CorTs, which are at 126 degrees and 267 degrees.

We consider the example of an eye that has asymmetric, nonorthogonal astigmatism, measured with the CSO Sirius tomographer (Costruzione Strumenti Oftalmici, Firenze, Italy). Figure 1 shows the total corneal power data as a map. The manifest refraction of this eye was −1.00/+2.25 × 115 degrees at a back vertex distance of 12.5 mm, which becomes −0.99/+2.26 × 115 degrees at the corneal plane. The CorT is 1.90 D with a steep meridian at 102 degrees. The hemiCorTs are 1.91 D with a steep meridian at 126 degrees and 2.90 D with a steep meridian at 267 degrees. These CorTs are shown graphically in Figure 2, on a polar plot that is divided at the hemidivisional boundary.

For each hemidivision, the hemidivisional treatment required to regularize the cornea is the vector difference between the hemiCorT and the CorT (see Figure, Supplemental Digital Content 3, http://links.lww.com/ICO/A601). To change hemiCorT$_1$ (1.91 D at 126 degrees) to the CorT (1.90 D at 102 degrees), the required hemidivisional treatment is 1.55 D of flattening at 158 degrees (TIA: 1.55 D Ax 68 degrees). On the other hemidivision, a hemidivisional treatment of 1.55 D of flattening at 248 degrees (TIA: 1.55 D Ax 158 degrees) is required. Note that the 2 hemidivisional treatments are of equal magnitude and at 90 degrees to each other, meaning that the combination of the 2 is overall astigmatically neutral to the refractive cylinder as intended. The regularization component of the treatment is shown in Figure 3A. This treatment has been constructed by applying

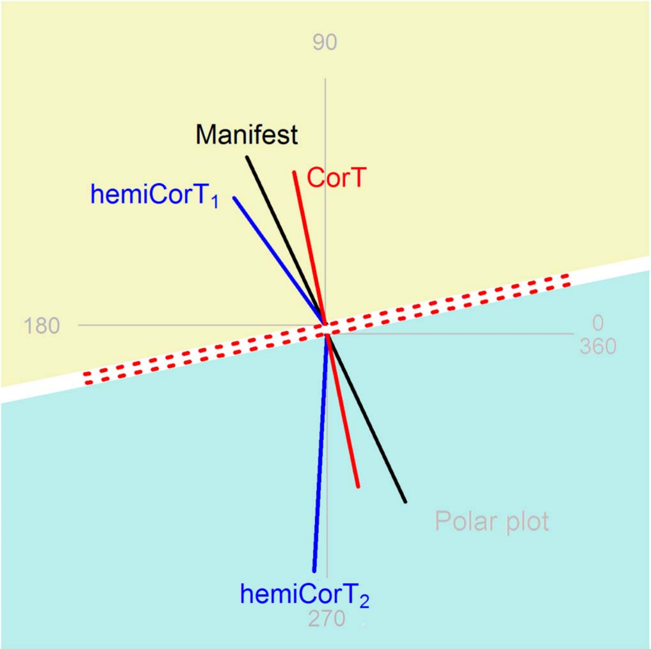

FIGURE 2. Summary of CorT and hemiCorT magnitudes and orientations, and the manifest refractive positive cylinder. The diagram has been divided at the corneal hemidivisional boundary (double red dotted lines), which is by definition perpendicular to the CorT. The CorT and the manifest refractive cylinder are shown in both hemidivisions to allow each hemidivision to be considered separately.

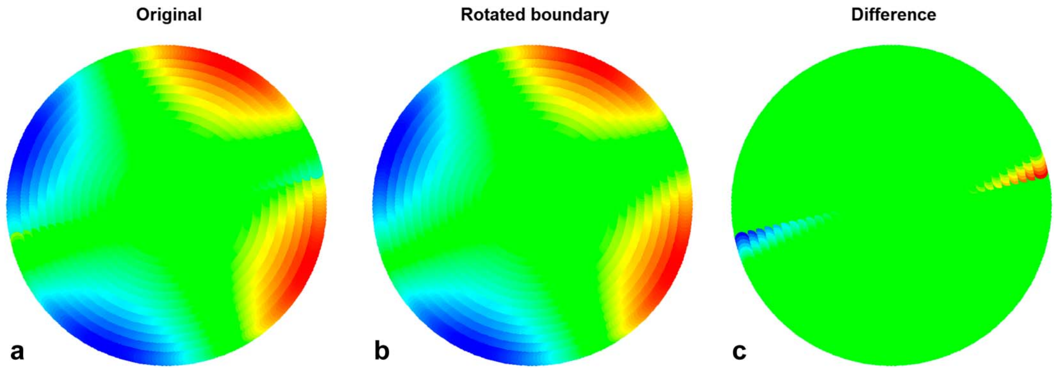

FIGURE 3. A, Change in total corneal power due to the regularization component of the treatment. The red areas correspond to the TIAs at axes of 68 degrees and 158 degrees, and the blue areas correspond to the areas of relative flattening 90 degrees away from these TIAs. B, Regularization component of the treatment after the notional boundary has been rotated to 23 degrees, which is halfway between the 2 areas of steepening. C, Difference in power between the original regularization and the altered regularization with the rotated notional boundary. The difference in power is antisymmetric, which means that no astigmatism is induced by the rotation of the notional boundary.

each astigmatic treatment to its corresponding corneal hemidivision without any blend zone.

One problem with the regularization shown in Figure 3A is that there is a discontinuity in the treatment profile right at the hemidivisional boundary. Two simple techniques that can be used to remove this discontinuity without inducing any extra astigmatism: 1) rotating the nominal boundary between the 2 hemidivisional treatments to the meridian that bisects the TIAs (Fig. 3B) or 2) using a technique to smooth a transition zone on either side of the hemidivisional boundary, like a convex combination with boundary conditions. For this example, we rotate the boundary. The difference in the profile between Figure 3A and 3B is antisymmetric (Fig. 3C), which shows that no astigmatism is being induced by the rotation of the boundary.

A Zernike decomposition of the regularization component of the treatment (after rotation of the boundary) shows:

1. A reduction in first-order components (tilt, tip),
2. A reduction in third-, fifth-, and seventh-order coma, and
3. An increase in third- and fifth-order trefoil and fifth-order pentafoil.

The regularization component of the treatment is responsible only for the changes in the odd-numbered orders and causes a 22% reduction in the root-mean-square wavefront error for the combined third-, fifth-, and seventh-order terms.

If we chose to neutralize the CorT, we would require 1.90 D of flattening at 102 degrees (TIA: 1.90 D Ax 12 degrees), but this would leave 1.03 D of manifest refractive cylinder uncorrected. Similarly, if we chose to neutralize the manifest refraction, we would require 2.26 D of flattening at 115 degrees (TIA: 2.26 D Ax 25 degrees), but this would leave 1.03 D of astigmatism on the cornea. Using vector planning with an emphasis of 60% manifest refractive cylinder corrected and 40% corneal astigmatism corrected, we derive a treatment of the regularized cornea with an astigmatic TIA of 2.06 D Ax 20 degrees (see Figure, Supplemental Digital Content 4, http://links.lww.com/ICO/A602). The combination of the 2 hemidivisional regularization treatments and the overall single astigmatic reduction treatment gives hemidivisional treatments of 2.44 D of flattening at 130 degrees (TIA: 2.44 D Ax 40 degrees) and 2.72 D of flattening at 273 degrees (TIA: 2.72 D Ax 3 degrees). The refractive cylinder target is +0.41 D × 143 degrees (at the corneal plane), and the corneal astigmatism target is 0.62 D at 53 degrees (see Figure, Supplemental Digital Content 5, http://links.lww.com/ICO/A603). Figure 4

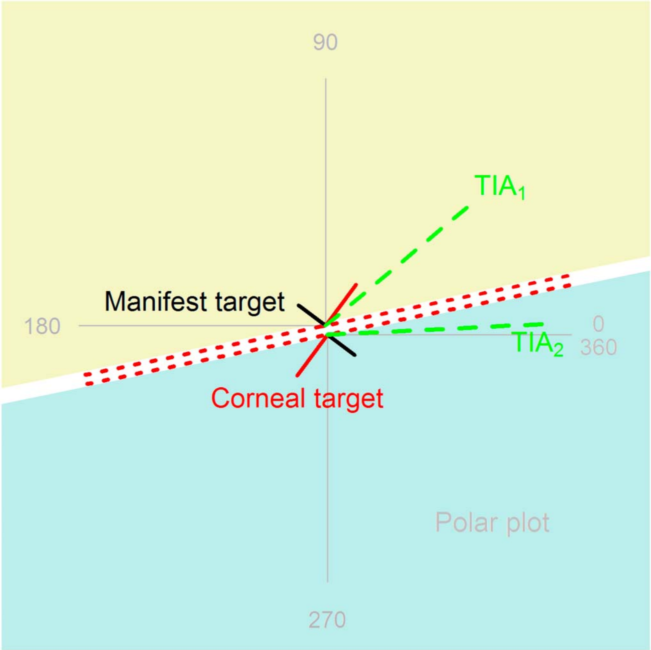

FIGURE 4. Summary of the combined hemidivisional treatments (TIA_1 and TIA_2), the manifest refractive positive cylinder target, and the corneal astigmatism target, displayed on a polar plot. The refractive and corneal targets are shown in both hemidivisions to allow each hemidivision to be considered separately.

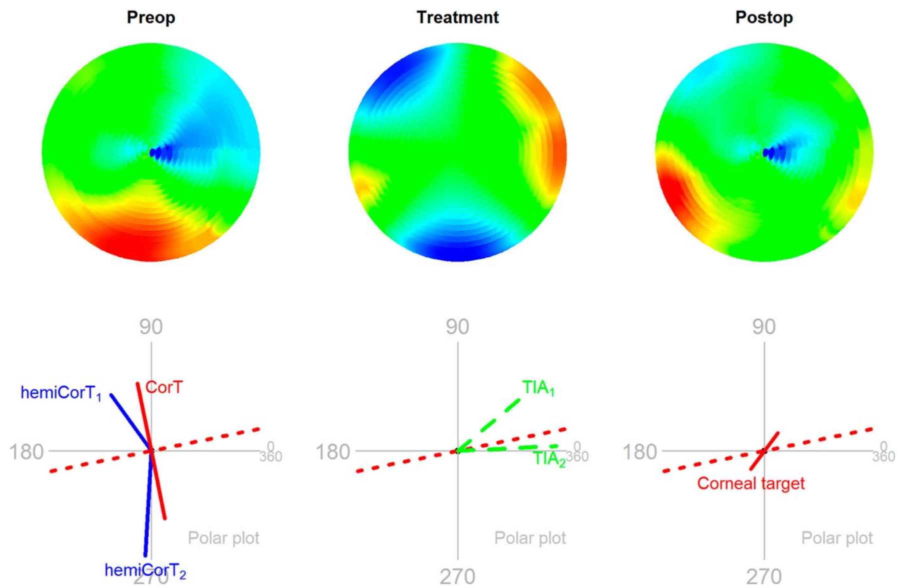

FIGURE 5. Total corneal power maps and polar plots corresponding to the preoperative measurement (left), the combined regularization and vector planning treatment (center), and the expected postoperative measurement (right).

summarizes the final hemidivisional treatments and the refractive and corneal targets on a polar plot. Figure 5 shows how the original total corneal power map is expected to be changed by the combined regularization and vector planning treatment.

In Figure 6 and Supplemental Digital Content 6 (see Figure, http://links.lww.com/ICO/A604) and Supplemental Digital Content 7 (see Figure, http://links.lww.com/ICO/A605), we show the effect of a purely refractive cylinder treatment with no regularization component. The TIA of 2.26 D Ax 25 degrees directly neutralizes the manifest refractive cylinder of +2.26 D × 115 degrees and targets a corneal astigmatism of 1.03 D at 53 degrees. Because there is no regularization component, the amount of corneal irregularity as measured by topographic disparity remains unchanged, and thus there are 2 different hemidivisional corneal astigmatism targets: 0.84 D at 177 degrees for the superior hemidivision and 2.49 D at 242 degrees for the inferior hemidivision.

Thus, treating by refractive cylinder alone would leave a corneal astigmatism of 1.03 D with hemidivisional components of 0.84 D and 2.49 D and a topographic disparity of 3.10 D. However, using the technique of regularization and reduction with vector planning, the remaining corneal astigmatism would have zero topographic disparity and 0.62 D in magnitude, with a 0.41 D of refractive cylinder remaining.

Figure 7 shows the how the original total corneal power map is expected to be changed by the pure refractive treatment.

DISCUSSION

We have shown how hemiCorTs allow a surgeon to plan a treatment that simultaneously regularizes and reduces idiopathic asymmetric nonorthogonal astigmatism. The treatment paradigm detailed in this article differs from many other treatments of irregular astigmatism; those were designed to address local irregularity,[13,19–21] often after previous corneal surgery or disease, whereas our paradigm is intended for use with healthy virgin eyes that have asymmetric or nonorthogonal astigmatism or both, as part of the astigmatic condition associated with a spherical refractive error. Potentially, most astigmatic eyes undergoing refractive surgery for spherocylindrical errors would have some level of asymmetric astigmatism because very few are perfectly regular. Treatment paradigms dealing with local nonuniform irregularity are unsuitable for such eyes, because they are not

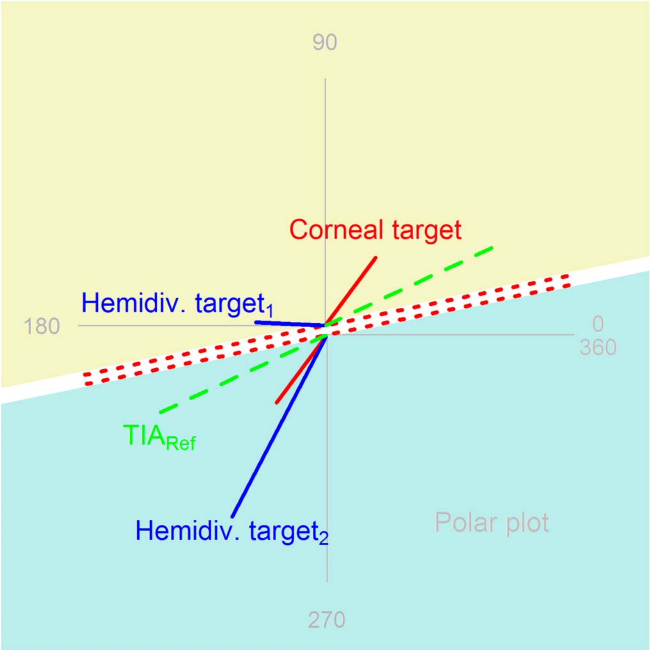

FIGURE 6. Summary of the pure refractive treatment (TIA$_{Ref}$), the hemidivisional astigmatism targets (Hemidiv. target$_1$ and Hemidiv. target$_2$) and the corneal astigmatism target, displayed on a polar plot. The refractive treatment and the corneal target are shown in both hemidivisions to allow each hemidivision to be considered separately.

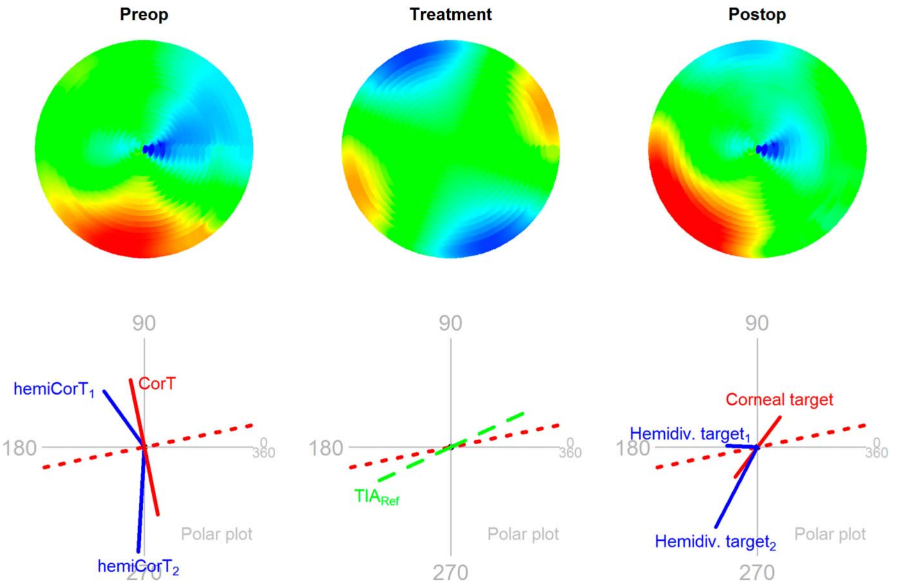

FIGURE 7. Total corneal power maps and polar plots corresponding to the preoperative measurement (left), the pure refractive treatment (center), and the expected postoperative measurement (right).

designed to target a regular astigmatic outcome across the whole cornea.

Gayton[3] described in detail how to use asymmetric nonorthogonal astigmatic keratotomy to address a number of different types of asymmetric nonorthogonal astigmatism. One of the problems that he mentions is that his topography software, back in 1996, did not compute the "percentage of the total astigmatism at each axis," and thus he was required to estimate where the axes (meridia) of astigmatism were for each corneal hemidivision and the amount of astigmatism at each of the axes. Gayton considered that the metrics available to him, namely "simulated keratometry values within different zones," were useful but not sufficient for fully determining all parameters for an asymmetric surgical treatment. Little has changed in the provision of measurements needed to plan treatments of asymmetric nonorthogonal astigmatism, possibly because such procedures have never become popular. We believe that hemidivisional CorT measurements can remove the need for the surgeon to estimate the orientation and magnitude of hemidivisional astigmatism, and that the method outlined in this article allows the surgeon to plan the asymmetric treatments directly with greater precision.

The regularization treatment described in this article is a combination of 2 hemidivisional astigmatism treatments that are oriented at 90 degrees to each other. This combination regularizes corneal astigmatism, with a side effect of increasing the contribution of third- and fifth-order trefoil and pentafoil components but decreasing the contribution of third-, fifth-, and seventh-order coma components. This trade-off between trefoil and coma components is likely to improve visual acuity because Zernike polynomials near the edge of the Zernike pyramid (like trefoil) impact visual acuity less than those at the center (like coma).[10,11] In addition, the combined root-mean-square wavefront error for third-, fifth-, and seventh-order Zernike terms decreases, which itself should lead to improved visual acuity.

Currently, most corneal topographers provide 2 steep and 2 flat corneal curvature values for 3-, 5-, and 7-mm diameter zones. These seem to represent the extreme curvature values measured in each zone. It would be possible to use these to determine 2 astigmatism values, for example, by pairing up the steep and flat measurements and calculating the 2 differences in dioptric power. However, such an arbitrary approach cannot be guaranteed to result in corneal astigmatism values that are reliable because irregular astigmatism may result in localized areas of extreme flatness or steepness. The CorT, both whole-of-eye and hemidivisional, gives a reliable measure of corneal astigmatism that is robust to local irregularity and deals with asymmetric nonorthogonal astigmatism in a systematic intuitive manner.

The principal treatment methodologies for irregular astigmatism are broadly classified as wavefront-guided or topography-guided. Wavefront-guided treatments rely on ocular wavefront measurements, which are problematic for a number of reasons, including that they may both be unreliable and restricted to the pupil size (meaning that important information about corneal irregularity may remain unmeasured).[22] Also, it is standard practice that the spherocylinder as measured by wavefront aberrometry is verified against manifest refractive measurements for plausibility and rejected if not within certain ranges of the sphere, cylinder, and axis, indicating the possible unreliability of wavefront measurements, especially in irregular corneas. In addition, the principle of correcting whole-of-eye irregular astigmatism on the cornea has been questioned by Murta and Rosa[23] and Alpins.[24] In contrast, topography-guided treatments are designed to treat corneal irregularity directly while ignoring noncorneal components of irregular astigmatism. However, topography-guided treatments have shown a tendency to undercorrect both spherical and cylindrical refractive errors.[13,20,21] Much of the trouble here arises from the use of a treatment paradigm that is radically different from a standard refractive paradigm used for treating spherocylindrical errors, which means that the commonly used laser nomograms targeting emmetropia are not applicable. Our method, presented in this article, has the advantage that it should be possible to use ablation profiles very similar to standard profiles normally used to treat spherocylindrical refractive errors, and thus, the existing laser nomograms should still apply with the ability to target a defined spherocylindrical outcome.

In the example, we showed 2 possible treatment strategies: the first was a theoretical combined regularization and vector-planned astigmatic reduction treatment; the second was a pure refractive treatment based on the manifest spherocylindrical error, much like is performed by most conventional surgeries now using purely refractive parameters. The vector-planned treatment aimed for a cornea with a minimum amount of regular astigmatism, while allowing a small amount of refractive astigmatism to remain (with a spherical equivalent of zero). The second conventional strategy aimed for zero refractive cylinder, ignoring the corneal irregularity and causing excess astigmatism to be left on the cornea in an irregular state.[16] Such a strategy is known to yield good refractive results but possibly leaves the patient with more intangible symptoms such as haloes and glare and no likely gain in best-corrected visual acuity. In this article, we presented the 2 strategies as alternatives, but in practice, the first strategy cannot be performed using today's excimer laser devices because no company currently supports hemidivisional asymmetric non-orthogonal treatment. Our hope is that excimer laser manufacturers will allow surgeons to specify hemidivisional treatments in the not-too-distant future now that a paradigm exists. Further studies would then be possible to apply this novel technique to suitable eyes in the refractive surgery process, to determine how much visual benefit is gained by adding astigmatism regularization to the refractive surgery process.

Because the method of regularization described in this article should end up being astigmatically neutral, we have not made any assumptions about the type of astigmatism reduction that is performed concurrently. We mentioned in the methods section that both a standard refractive treatment and a vector-planned treatment would be suitable. In practice, the amount of measured refractive astigmatism remaining after vector planning has been found to be less than expected,[16,18] possibly because the corneal shape is less astigmatic than if treated by refractive parameters alone. The choice between a standard refractive treatment and a vector-planned treatment should depend on the orientations of the target manifest refractive cylinder and target corneal astigmatism, as well as the amount of ocular residual astigmatism[5] present. If possible, an emphasis between corneal and refractive targets should be chosen to avoid obliquely aligned targets.

The example given in this article was purposely a case in which the amount of corneal irregularity was small, similar to the majority of cases. It would certainly be possible to apply the same methodology to cases that have larger amounts of global irregularity, but there are a number of reasons to be cautious about such cases. First, corneas with a large amount of corneal irregularity, especially those occurring after previous ocular surgery, may have shapes that are unstable, which makes the concept of a finely customized treatment less meaningful. Second, when there is large separation between the visual axis and corneal apex, there is some evidence to believe that a treatment away from the visual axis, toward the corneal apex, might reduce the magnitude of induced higher-order aberrations.[25] However, it is unclear how this would interact with the CorT, which is currently based on the visual axis because of the way that the raw topographic/tomographic data are exported, especially if the position of the corneal apex is not stable. In the future, we aim to study the applicability of our proposed method to eyes with forme fruste keratoconus.

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