New method of quantifying corneal topographic astigmatism that corresponds with manifest refractive cylinder

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PURPOSE: To derive a method of quantifying corneal topographic astigmatism (CorT) that accurately represents manifest refractive cylinder.

SETTING: Private practice, Melbourne, Australia.

DESIGN: Retrospective study.

METHOD: Axial power measurements obtained using topography in right eyes and left eyes were analyzed. For each Placido ring, an astigmatism value was calculated. The ring astigmatism values were combined via vector summation to create a new measure termed CorT. This parameter was assessed against other commonly used measures of corneal astigmatism using the ocular residual astigmatism (ORA) and its standard deviation (SD) on how closely each measure matched manifest refractive cylinder. The flat meridian of the CorT can also be used to conceptually divide the cornea into 2 hemidivisions and a CorT value subsequently calculated for each hemidivision of the cornea.

RESULTS: The CorT was assessed against other commonly used measures of corneal astigmatism using the ORA (0.62 diopters [D] $\pm$ 0.33 [SD]) and had better correlation with manifest refractive cylinder than manual keratometry (K) (ORA 0.68 $\pm$ 0.38 D), simulated K (ORA 0.70 $\pm$ 0.35 D), corneal wavefront (ORA 0.74 $\pm$ 0.36 D), and paraxial curvature matching (ORA 0.85 $\pm$ 0.48 D). The SD of the ORA for CorT was significantly less than the other measures of astigmatism (P<.001).

CONCLUSIONS: An alternative measure of corneal astigmatism, known as CorT, corresponded better to manifest refractive cylinder than other commonly used measures. A hemidivisional CorT can also represent the nonorthogonal asymmetrical astigmatism in irregular corneas.

Financial Disclosure: Dr. Alpins and Mr. Stamatelatos have a financial interest in the ASSORT software program used to support the planning and analysis of astigmatic correction. Dr. Ong is an employee of ASSORT.

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When treating astigmatism in refractive laser surgery, it is important that the surgeon not only has an accurate measure of the refractive cylinder but also of the corneal astigmatism. In the ideal situation, these would be exactly the same. In conventional excimer laser surgery, it is the refractive cylinder that is being ablated onto the cornea, which in many cases is not the same in magnitude and/or orientation as the corneal astigmatism. If these differences are significant, this may lead to suboptimal visual outcomes.[1,2] The better the correlation between the magnitude and the orientation of the corneal astigmatism and refractive cylinder, the less astigmatism will be left remaining in the optical system of the eye as a whole after treatment. The difference between the corneal and refractive measures of astigmatism is precisely described by the ocular residual astigmatism (ORA) and is defined as the vectorial difference between the corneal astigmatism and the refractive cylinder at the corneal plane.[3] In some cases, the magnitude of corneal astigmatism can increase after excimer laser surgery as a consequence of the treatment being based on spherocylindrical refractive parameters alone, without considering the amount and orientation of the corneal astigmatism, which results in increasing aberrations and decreasing the visual quality achieved.[1,4]

Corneal topography maps customarily display a simulated keratometry (K) (designated as SimK on

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some devices) value, which is a quantitative descriptor of corneal astigmatism near the 3.0 mm zone. It was used as an attempt to gain equivalence to corneal keratometry at the time of the introduction of the computer-assisted videokeratography technology in the 1980s.[5–7]

One commonly encountered difficulty with the simulated K value is that the magnitude and meridian calculated by the device are based on data taken from a narrow annulus in the 3.0 mm region of the cornea and hence may not be an accurate representation of the existing corneal astigmatism as manifested in refractive cylinder, which measures the total astigmatism of the eye including nonoptical cortical perception. In this paper, we describe a vectorially calculated parameter, corneal topographic astigmatism (CorT), which is derived from a wide annular region on the cornea. Ideally, this measure would precisely correspond to the corneal plane refractive cylinder because corneal astigmatism is a major contributor to the total astigmatism of the visual system.[3] The CorT value is also intended to provide a consistent measure of corneal astigmatism across regular and irregular corneas, which can then be implemented in corneal incisional and refractive laser surgery to better correct astigmatism. To our knowledge, this technique has not been described before.

Furthermore, we describe an extension of CorT methods that allows hemidivisional CorTs to be derived for the 2 hemidivisions of the cornea. These allow a standardized measure of corneal irregularity, known as topographic disparity (TD), to be calculated for nonorthogonal asymmetric corneas. The TD is calculated as the vectorial difference between the 2 hemidivisional CorTs on a 720-degree double-angle vector diagram and effectively addresses nonorthogonal and asymmetric components of irregularity in healthy astigmatic corneas. The 2 hemidivisional CorT values are also necessary when assessing separate sections of the cornea for pathological process such as ectasia or for treatment with excimer lasers using the vector-planning asymmetric treatment process.[8–10]

SUBJECTS AND METHODS

Study Data

Refractive, keratometric, and topographic astigmatism data were assessed retrospectively for virgin right eyes and virgin left eyes that later proceeded to have refractive laser surgery. Measurements were performed between June 2009 and August 2011. Right-eye data and left-eye data were analyzed separately to ensure that observations were independent. Keratometric data were measured with an OM-4 keratometer (Topcon Corp.).

Topographic data were captured with an Atlas 9000 corneal topography system (Carl Zeiss Meditec) and exported using the "export for research" function available in version 3.0.0.39 of the software. The exported data included axial curvature measurements at 180 points on 22 Placido rings with varying diameters. The innermost ring (ring 0) has an equivalent diameter on the cornea of approximately 0.8 mm, and the outermost ring (ring 21) has an equivalent diameter on the cornea of approximately 11.0 mm. The rings are spaced almost evenly, except for a slightly increased separation between ring 7 and its 2 neighboring rings. Data for rings 18 to 21 were discarded because the data for each ring were incomplete for every eye in the dataset.

The mean ORA for the 5 corneal measures, specifically the standard deviations (SD) of the ORA magnitudes were compared across patients' eyes. Furthermore, for the 5 corneal measures of astigmatism, the mean magnitude of the ORA and the corneal astigmatism magnitudes to refractive cylinder magnitudes were also compared.

To derive CorT, a complete comparison of all contiguous sets of rings was performed to find the set of rings with the lowest SD of the ORA. To account for any dependence of the SD of the ORA on the sample, the distribution of the SD of the ORAs was estimated from 1000 bootstrap samples.

Corneal Topographic Astigmatism

The CorT value was calculated as a summated vector mean of the astigmatism values determined from a large number of adjacent concentric Placido rings. First, this paper reviews how to determine the astigmatism by finding the best-fit spherocylinder to axial power measurements taken from each single ring. It then details how to combine multiple corneal astigmatism estimates via a summated vector mean of their individual values.

Taking the axial curvature measurements for a particular ring, to fit a spherocylinder to this data it is necessary to perform a least-squares fit of the following form:

$$P(\theta) \sim S + C\cos^2(\alpha - \theta)$$

where the measured power P at meridian α is fit with a perfect spherocylinder with a spherical component with power S and a cylindrical component with power C and meridian θ. Here, if C is positive, θ refers to the steep meridian; however, if C is negative, θ refers to the flat meridian. Figure 1 shows an example of such a fit.

The fitted spherocylinder is called Ring.#.K (ranging from Ring.0.K to Ring.21.K in this case). Note that the simulated K produced by the Atlas 9000 topographer is exactly the same as Ring.7.K.

To calculate a CorT, the summated vector mean of selected Ring.#.Ks must be calculated. Mathematically, the process is as follows:

1. Represent the cylindrical component of each Ring.#.K as a double-angle vector.[4] For a Ring.r.K with a cylindrical component C_r at meridian θ_r, the double angle vector v_r is

$$v_r = (C_r \cos 2\theta_r,\ C_r \sin 2\theta_r)$$

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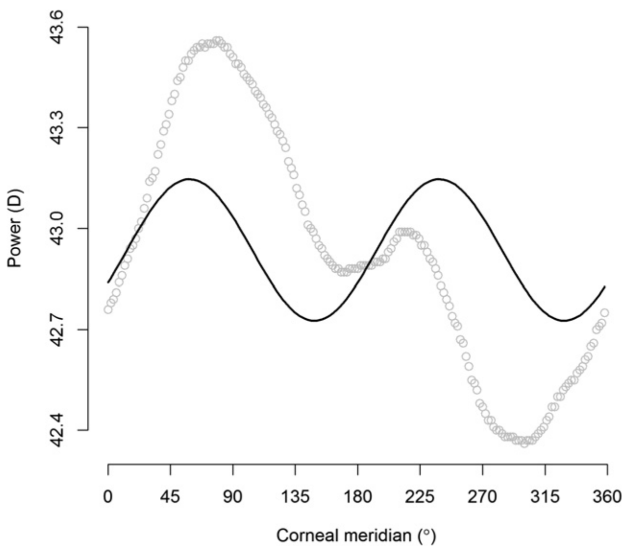

Figure 1. Spherocylindrical fit to corneal power data taken from ring 7. Open circles are data, and the continuous line is the spherocylindrical fit. The data look substantially different from the fitted curve because the cornea is highly irregular with asymmetric and nonorthogonal components.

Calculate the summated vector mean v_{Mean} of the double angle vectors

$$V_{Mean} = \frac{\sum_{r \in R} v_r\, p_r}{\sum_{r \in R} p_r}$$

where R is the set of rings chosen and p_r is the proportion of measurements in ring r that are valid. The presence of the factor p_r ameliorates the influence of missing data on the summated vector mean. If there are no missing measurements in any of the chosen rings, the summated vector mean reduces to

$$V_{Mean} = \frac{\sum_{r \in R} v_r}{|R|}$$

where $|R|$ is the number of rings chosen.

2. Convert the double-angle vector mean back to a cylinder power and meridian

$$C_{Mean} = \sqrt{(v_{Mean_x})^2 + \left(v_{Mean_y}\right)^2}$$

$$\theta_{Mean} = \frac{1}{2}\tan^{-1}\frac{v_{Mean_y}}{v_{Mean_x}}$$

3. Calculate the mean keratometric component of the final CorT as an average of the mean keratometric components of the selected Ring.#.Ks

$$K_{Mean} = \frac{\sum_{r \in R} K_r p_r}{\sum_{r \in R} p_r}$$

In the results section, what rings to be used is determined by performing a complete comparison of all contiguous sets of rings.

It is recommended that this method be undertaken for each different topographer using all accurate ring data available to determine which rings will be used for calculating the CorT.

Example of Generating a Corneal Topographic Astigmatism from Multiple Ring.#.Ks

Assume that we want to use only rings 4, 8, and 12 to generate a CorT and that there are no missing measurements in any ring.

Ring.4.K is 42 D/43 D with the steep meridian @ 80.
Ring.8.K is 42 D/44 D with the steep meridian @ 60.
Ring.12.K is 42 D/43.7 D with the steep meridian @ 30.

The double angle vectors for the cylindrical components of Ring.4.K, Ring.8.K and Ring.12.K are (−0.94, 0.34) and (−1.00, 1.73) and (0.85, 1.47) respectively. The mean is

$$\frac{(-0.94, 0.34) + (-1.00, 1.73) + (0.85, 1.47)}{3} = (-0.36, 1.18)$$

which translates to 1.24 D with the steep meridian @ 53.

The mean keratometry component of CorT is

$$\frac{42.5 + 43 + 42.85}{3} = 42.78$$

Therefore, CorT is 42.16/43.40 with the steep meridian @ 53. Figure 2 shows this calculation diagrammatically.

Ring Weighting

It is possible to alter the relevance importance of each ring by using a weighting factor and calculating the weighted summated vector mean. If each ring r has weighting w_r, the weighted summated vector means become

$$v_{Mean} = \frac{\sum_r w_r\, v_r\, p_r}{\sum_r w_r p_r}$$

$$K_{Mean} = \frac{\sum_r w_r\, K_r\, p_r}{\sum_r w_r\, p_r}$$

This is explained further in the discussion.

Extending Corneal Topographic Astigmatism to Hemidivisional Analysis

Previously, Alpins[9] described dividing an irregular cornea conceptually into 2 hemidivisions, with 2 corresponding astigmatisms that have separate distinct semimeridia. To ensure that this representation is consistent for all corneas, it is necessary to divide the cornea in a functional systematic way that also works for irregularity in both healthy and pathological astigmatic corneas. If the semimeridia are considered to be aligned in the orientation of the 2 steep meridia, an effective way to divide the cornea equally is along the flat meridian of the overall CorT. After dividing the cornea into 2 hemidivisions, the hemidivisional Ring.#.Ks and CorTs can be calculated just like normal complete Ring.#.Ks and CorTs, except that each calculation is based only on data taken from 1 hemidivision. (Refer to Figure 3 for the relationship between raw data and hemidivisional Ring.#.Ks.) The double-angle vector difference between the hemidivisional CorTs is the measure of corneal irregularity known as TD.[8–10] Note that the summated vector mean of the

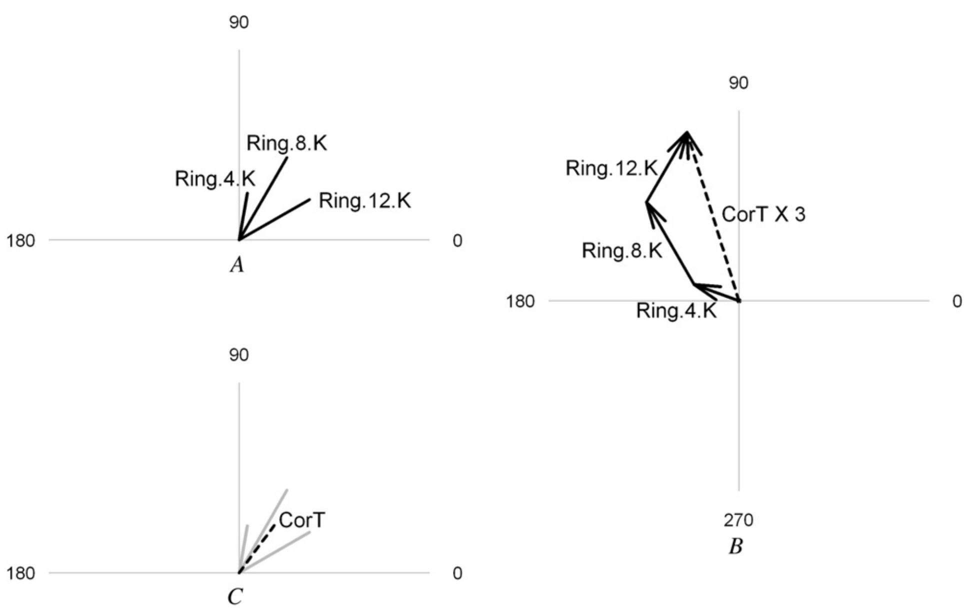

Figure 2. Illustration of summated vector mean. *A*: Original Ring.#.Ks are shown on a polar diagram. *B*: The double-angle vector representations of the Ring.#.Ks are shown as solid lines where the angles have been doubled but the magnitudes remain unchanged. The summated vector sum, which in this case of 3 components is 3 times the length of the summated vector mean, is shown as a dashed arrow. *C*: The resulting actual CorT on a polar diagram as it would occur on the cornea is shown as a dashed line one third the length displayed in *B* (CorT = corneal topographic astigmatism).

2 hemidivisional CorT components is exactly the CorT calculated for the whole cornea.

Corneal Wavefront Astigmatism

An alternative way to generate a representation of corneal astigmatism is from the Zernike coefficients Z(2,2) and Z(2,−2) of the simulated corneal wavefront data generated by the topographer. Here, this representation is referred to as corneal wavefront astigmatism (CorW). Zernike coefficients Z(2,2) and Z(2,−2) taken together are equivalent to the double-angle vector representation of the cylindrical component. The cylinder power and axis are

$$C_{wavefront} = \frac{4\sqrt{6}}{r^2}\sqrt{\left(Z_2^{-2}\right) + \left(Z_2^{2}\right)^2}$$

$$\theta_{wavefront} = \frac{1}{2}\tan^{-1}\frac{Z_2^{-2}}{Z_2^{2}}$$

where *r* is the pupil radius.

In this data set, the Atlas topographer used a value of $r = 3.0$ mm when generating its Zernike coefficients.

Paraxial Curvature Matching Astigmatism

Thibos et al.[11] suggest that the corneal wavefront measure CorW, which is based only on 2nd-order Zernike terms, may not effectively match subjective refraction for spherocylinder. Their alternative, the method of paraxial curvature matching (PCM), takes higher-order Zernike coefficients into account. The CorW and PCM values differ because of the way that the best-fit spherocylinder is derived; with CorW, the spherocylinder is derived by finding the best fit to the measured axial powers, whereas PCM derives its spherocylinder by matching the curvature of the corneal wavefront.

If Zernike orders up to 6 are used, the cylinder power and axis are

$$C_{PCM} = \frac{2}{r^2}\sqrt{\left(-2\sqrt{6}Z_2^{2} + 6\sqrt{10}Z_4^{2} - 12\sqrt{14}Z_6^{2}\right)^2 + \left(-2\sqrt{6}Z_2^{-2} + 6\sqrt{10}Z_4^{-2} - 12\sqrt{14}Z_6^{-2}\right)^2}$$

$$\theta_{PCM} = \frac{1}{2}\tan^{-1}\left(\frac{-2\sqrt{6}Z_2^{-2} + 6\sqrt{10}Z_4^{-2} - 12\sqrt{14}Z_6^{-2}}{-2\sqrt{6}Z_2^{2} + 6\sqrt{10}Z_4^{2} - 12\sqrt{14}Z_6^{2}}\right)$$

where *r* is the pupil radius and PCM is PCM. Again, $r = 3.0$ mm for our measurements.

Evaluation of Measures of Corneal Astigmatism Against Manifest Refractive Cylinder

Corneal astigmatism was measured using manual K, computer-assisted videokeratography (simulated K), corneal wavefront aberrometry (CorW), and paraxial curvature matching (PCM). The CorT value was derived from the axial power data measured by the videokeratograph. To evaluate these 4 different measures of corneal astigmatism, the ORA for each of them was calculated. The ORA is the vectorial difference between each measure and the manifest refractive cylinder at the corneal plane.[3] The authors support the use of manifest refractive cylinder as a benchmark for overall astigmatism for the following reasons:

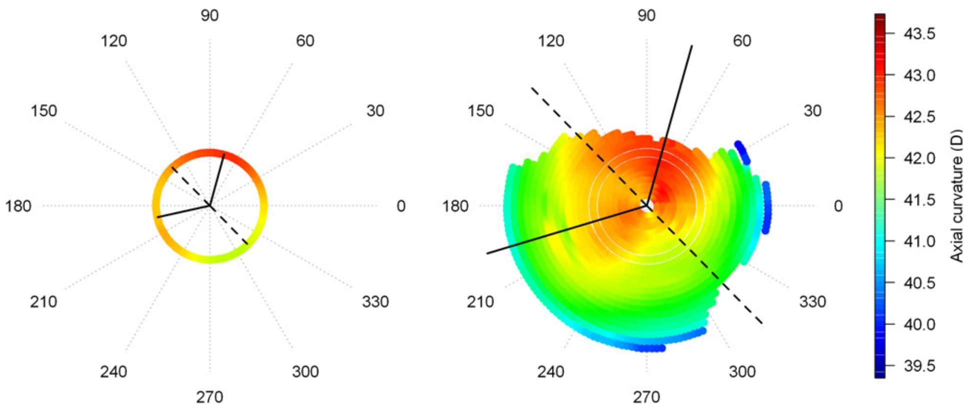

Figure 3. Axial curvature data. The left image shows ring 7 alone, and the right image shows all the measured data. The dashed lines show the division meridian at 134 degrees and 314 degrees, and the solid lines show the semimeridia of the hemidivisional Ring.7.Ks (*left*) and CorTs (*right*).

1. Manifest refractive cylinder is a measure of the total ocular (corneal and internal) and perceived (visual cortex) cylinder.
2. Most excimer laser treatments are currently based on manifest refractive parameters, confirming manifest refractive cylinder as the most relevant current measure of corneal plane visual correction.
3. Those treatments that are derived from ocular wavefront measurements use manifest refraction as a benchmark for treatment confirmation.
4. Eyes with lower ORA magnitudes tend to have better visual outcomes after refractive surgery.[1,2]

Clinically Relevant Parameters to Compare Corneal Astigmatism and Manifest Refractive Cylinder Measures

1. *Variability in the ORA magnitude determined by standard deviation (SD).* Any measure of corneal astigmatism that can be used in corneal and refractive assessment, and surgery should preferably match the manifest refractive astigmatism (at the corneal plane). Although the net polar value of the ORA can be described on average by Javal's rule,[12] there is variability in the ORA and its net polar value between eyes.[13] The variability in the ORA magnitude arises from 2 independent sources; that is, variability in ORA between eyes together with measurement variability (both systematic and random) of the corneal astigmatism and refractive cylinder. For a given set of eyes, the intereye variability cannot be influenced, which means that any variability in the ORA magnitude for this sample must be due to changes in the corneal parameters because the individual refractive cylinder is common to all 4. Any trend in measurement variability can be excluded as a systematic factor by examining its summated vector mean, which Goggin et al.[14] identified as being random due to its low magnitude, compared with the summated vector mean of incisional surgically induced astigmatism of the order of 0.50 D, which was a multiple of 6 times larger. Thus, reduced variability in the ORA magnitude indicates an improved consistency in match between corneal astigmatism and manifest refractive cylinder across different patients, a lower value being preferable. Bootstrapping was performed to quantify the amount of variability across different sample populations.
2. *Mean magnitude of the ORA.* In clinical practice, the magnitude of the ORA is the principal consideration to evaluate the correlation between corneal and refractive astigmatism, which includes both magnitude and orientation in the assessment. A low magnitude value of ORA indicates closeness of corneal and refractive parameters. This determines what proportion of the preoperative astigmatism can be surgically fully treated because the ORA will be the amount of astigmatism that will be targeted to remain in the optical system of the eye on the cornea, in the manifest refraction, or both. The mean ORA magnitudes corresponding to the 5 different corneal astigmatism measures were compared with their meridia (manual K; simulated K, which is the same as Ring.7.K; CorW; PCM; and CorT) to determine the correlation to manifest refractive cylinder, also taking into account the magnitude and the axis of the cylinder.
3. *Mean magnitude of corneal astigmatism value compared with manifest refractive cylinder.* What corneal astigmatism values are most representative of refractive function was determined by comparing these to the magnitude of the manifest refractive cylinder. Here, a close correspondence was specifically looked for as further evidence of the validity of the corneal astigmatism magnitude measurements.

RESULTS

The study assessed data in 486 virgin right eyes and 485 virgin left eyes of 498 subjects (190 men and 308 women; age 19 to 64 years). Twelve right eyes and 13 left eyes were excluded because more than 10% of the topographic data was missing from ring 7 (with a diameter of approximately 4.0 mm) due to upper lid interference; the incompleteness of the data could have led to unreliable simulated K measurements.

This section presents the results derived from right-eye data in detail. The results from left-eye data, which were found to be parallel, are summarized at the end of the section.

Right-Eye Data

Table 1 shows the 40 sets of ring groupings with the least variability in the ORA magnitude. Ring range 0 to 17, corresponding to using all available useful data, had the lowest SD of the ORA. However, most other sets in Table 2 had an SD of the ORA that was not significantly different than the lowest SD of the ORA. All

Table 1. Standard deviations of the ocular residual astigmatism magnitude for corneal topographic astigmatism derived from various contiguous sets of rings estimated using bootstrapping.

Ring Range	ORAsd mean D	95% of CI Difference from 0–17 Set	*P* Value* of Difference
0–17	0.331	—	—
0–16	0.332	−0.003, 0.004	0.42
0–15	0.333	−0.005, 0.009	0.25
1–17	0.334	0.000, 0.006	0.02
1–16	0.334	−0.001, 0.007	0.06
0–14	0.335	−0.006, 0.013	0.26
0–13	0.335	−0.009, 0.017	0.29
0–12	0.335	−0.011, 0.019	0.30
1–15	0.336	−0.002, 0.011	0.11
1–12	0.336	−0.010, 0.019	0.28
1–14	0.336	−0.005, 0.015	0.18
1–13	0.336	−0.008, 0.019	0.24
0–11	0.337	−0.011, 0.024	0.27
1–11	0.337	−0.011, 0.023	0.26
2–12	0.337	−0.009, 0.022	0.24
2–11	0.337	−0.010, 0.023	0.25
2–16	0.338	0.000, 0.012	0.02
2–13	0.338	−0.006, 0.021	0.17
2–14	0.338	−0.003, 0.017	0.11
2–15	0.338	−0.001, 0.015	0.05
2–17	0.338	0.001, 0.013	0.01
1–10	0.340	−0.010, 0.027	0.19
2–10	0.340	−0.010, 0.026	0.19
0–10	0.340	−0.009, 0.028	0.18
3–11	0.340	−0.008, 0.027	0.16
3–12	0.340	−0.006, 0.025	0.13
2–9	0.341	−0.010, 0.029	0.17
3–9	0.341	−0.009, 0.029	0.16
3–10	0.341	−0.008, 0.028	0.15
1–9	0.342	−0.008, 0.031	0.14
3–13	0.342	−0.003, 0.024	0.08
0–9	0.342	−0.008, 0.030	0.12
3–14	0.342	0.000, 0.022	0.02
3–15	0.343	0.002, 0.021	0.01
3–16	0.343	0.003, 0.020	0.00
3–8	0.344	−0.008, 0.033	0.13
2–8	0.344	−0.008, 0.033	0.11
4–9	0.344	−0.007, 0.033	0.11
4–11	0.344	−0.004, 0.030	0.08
3–17	0.345	0.004, 0.022	0.00

CI = confidence interval
*One sided

ring ranges with a low SD of the ORA include rings 3 to 8. For the analysis, CorT with the complete ring range 0 to 17 was generated because it preferentially included all in the range and the least variability.

Figure 4 shows the bootstrapped SD of the ORA values (estimated from 1000 bootstrap replications) for the Ring.#.Ks, manual K, simulated K, CorW, PCM, and CorT. The SD of the ORA values for the inner Ring.#.Ks (rings 0 to 2) and for the outer Ring.#.Ks (rings 14 to 17) are higher and more variable than those for the intermediate Ring.#.Ks (rings 3 to 13).

Table 2. The arithmetic and summated vector means of the ocular residual astigmatism magnitudes. Proportions of the ocular residual astigmatism summated vector mean to the arithmetic mean in the right column show consistent trends; none of these differences were statistically significant.

Parameter	ORA (D) Magnitude Arithmetic (Mean ± SD)	ORA (D) Summated Vector (Mean)	Magnitude Proportion (%)
Manual keratometry	0.68 ± 0.38	0.51 × 173	75
Simulated keratometry	0.70 ± 0.35	0.56 × 179	80
Corneal wavefront	0.74 ± 0.36	0.61 × 179	82
Corneal topographic astigmatism	0.62 ± 0.33	0.45 × 178	73

Mean Magnitude of Ocular Residual Astigmatism

Table 2 shows the mean ORA magnitudes. The CorT ORA values tended to be lower and more consistent (have lower variability) than the ORA values from other corneal measures. The closeness of the ORA summated vector mean to the mean ORA magnitudes shows a strong trend for the ORA orientation and magnitude and little random measurement error.

Variability in Ocular Residual Astigmatism Magnitude Determined by Standard Deviation

Table 3 shows confidence intervals for direct comparisons between the SD of the ORA for CorT and the SD of the ORA for manual K, simulated K, CorW, and PCM. The SD of the ORA for CorT is significantly lower than that from manual K, CorW, simulated K, and PCM.

Table 4 shows a comparison of ORA magnitude differences. The ORA magnitude difference for CorT was significantly lower than the ORA magnitudes from the 3 other measures.

Mean Magnitude of Corneal Astigmatism Compared to Refractive Cylinder

Table 5 shows the mean values for astigmatism and cylinder. The CorT values are significantly smaller and closer to the manifest refractive cylinder than the other corneal measures of astigmatism.

Table 6 compares the mean differences between the astigmatism magnitudes and refractive cylinder. The difference between CorT magnitude and refractive cylinder was significantly less than the differences of manual K, simulated K, and CorW magnitudes from refractive cylinder.

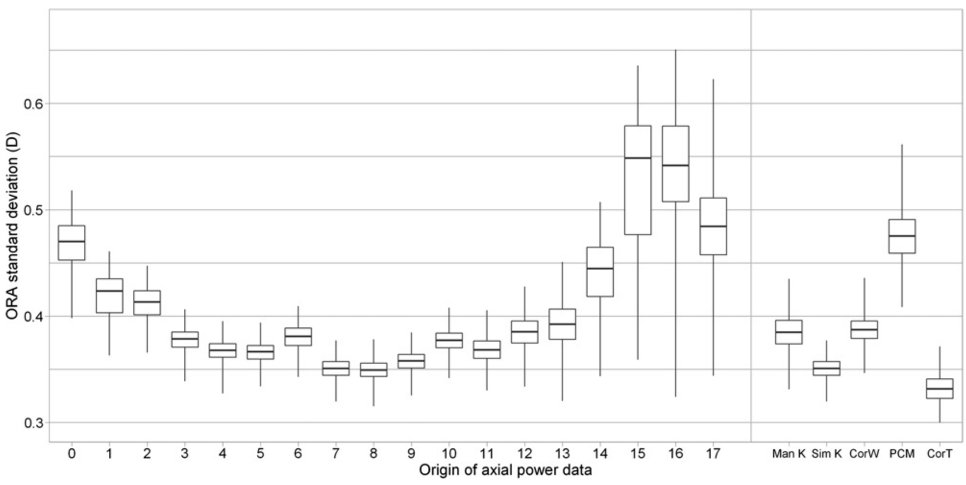

Figure 4. Bootstrapped standard deviations of the ORA magnitude. The boxplots labeled 0 to 17 are calculated from the corresponding Ring.#.Ks. The 5 boxplots labeled Man K, SimK, CorW, PCM, and CorT are calculated from manual K, simulated K (ring 7), CorW, PCM, and CorT derived from rings 0 to 17, respectively. The boxplots show the quartiles and extremes of the bootstrapped values. Corneal topographic astigmatism has the smallest value, corresponding to a lower variability of the ORA (Cor T = corneal topographic astigmatism; CorW = corneal wavefront astigmatism; ManK = manual keratometry; ORAsd = ocular residual astigmatism standard deviation; PCM = paraxial curvature matching; SimK = simulated keratometry).

Left-Eye Data

The best range of rings to generate CorT by examining the SD of the ORA mean was 0 to 17, and the best 40-ring ranges all included rings 4 to 10. The SD of the ORAs for the intermediate Ring.#.Ks (rings 3 to 12) are less than those for the inner Ring.#.Ks (rings 0 to 2) and the outer Ring.#.Ks (rings 13 to 17). The SD of the ORA for CorT was significantly less than the SD of the ORA for manual K, simulated K, CorW, and PCM astigmatism at the 5% confidence level. The mean ORA magnitudes corresponding to manual K, simulated K, CorW, CorT, and PCM were 0.67 D, 0.69 D, 0.74 D, 0.60 D, and 0.83 D, respectively, showing that the ORA magnitude for CorT was smallest (all raw bootstrapped *P* values < .001). The mean astigmatism magnitudes corresponding to manual K, simulated K, CorW, CorT, and PCM were 0.96 D, 1.02 D, 1.21 D, 0.84 D, and 1.22 D, respectively, showing that the CorT magnitude was the closest to the mean refractive cylinder magnitude of 0.81 D at the corneal plane.

Table 3. Difference between the ocular residual astigmatism SD for corneal topographic astigmatism and the ocular residual astigmatism SD for 4 other corneal measures of astigmatism estimated by bootstrapping. The 1-sided *P* values correspond to the null hypothesis that the ocular residual astigmatism SD for corneal topographic astigmatism is not less than the other ocular residual astigmatism SDs.

Parameter	Mean D	95% CI (D)	*P* Value*
Man K ORAsd – CorT ORAsd	0.057	0.018, 0.083	.001
Sim K ORAsd – CorT ORAsd	0.018	−0.003, 0.039	.045
CorW ORAsd – CorT ORAsd	0.026	0.003, 0.048	.014
PCM ORAsd – CorT ORAsd	0.127	0.083, 0.175	<.001

CI = confidence interval; CorT = corneal topographic astigmatism; CorW = corneal wavefront astigmatism; Man K = manual keratometry; ORAsd = ocular residual astigmatism standard deviation; PCM = paraxial curvature matching; Sim K = simulated keratometry
*One sided

Example of Generating Hemidivisional Corneal Topographic Astigmatisms

Figure 3 shows the axial curvature data for a virgin right eye with irregular astigmatism. Table 7 shows the Ring.#.Ks for this eye. For this example, equal weightings across all available rings were again used to calculate the overall CorT. The flat meridian of the CorT was at 134 degrees and 314 degrees, so the cornea

Table 4. Differences between the magnitude of the ocular residual astigmatism generated from corneal topographic astigmatism and the magnitude of the ocular residual astigmatism from manual keratometry, simulated keratometry, corneal wavefront astigmatism, and paraxial curvature matching estimated by bootstrapping. The 1-sided *P* values correspond to the null hypothesis that the corneal topographic astigmatism ocular residual astigmatism magnitude is not less than the other ocular residual astigmatism magnitudes.

Parameter	Mean D	95% CI (D)	*P* Value*
Man K − CorT	0.057	0.032, 0.085	<.001
Sim K − CorT	0.077	0.060, 0.097	<.001
CorW − CorT	0.118	0.101, 0.139	<.001
PCM − CorT	0.141	0.106, 0.176	<.001

CI = confidence interval; CorT = corneal topographic astigmatism; CorW = corneal wavefront astigmatism; Man K = manual keratometry; ORAsd = ocular residual astigmatism standard deviation; PCM = paraxial curvature matching; Sim K = simulated keratometry
*One sided

Table 5. Statistics for mean astigmatism and cylinder values.

Parameter	Mean Astigmatism Magnitude (D) ± SD	*P* Value*
Refractive cylinder at corneal plane	0.78 ± 0.76	
Manual keratometry	0.91 ± 0.74	<.001
Simulated keratometry	0.98 ± 0.69	<.001
Corneal wavefront	1.06 ± 0.75	<.001
Corneal topographic astigmatism	0.80 ± 0.58	<.001

*One sided

Table 6. Differences between the mean magnitudes of corneal astigmatism and the mean magnitude of refractive cylinder at the corneal plane, as estimated by bootstrapping.

Parameter	Mean Astigmatism Magnitude (D)	95% CI
Man K − refractive cylinder	0.137	0.087, 0.184
Sim K − refractive cylinder	0.201	0.149, 0.251
CorW − refractive cylinder	0.285	0.233, 0.336
CorT − refractive cylinder	0.018	−0.030, 0.069

CI = confidence interval; CorT = corneal topographic astigmatism; CorW = corneal wavefront astigmatism; Man K = manual keratometry; Sim K = simulated keratometry

was divided there. Table 7 also shows the new hemidivisional Ring.#.Ks. The semimeridia are shown overlaid on the axial curvature data in Figure 3. The CorT semimeridia at 74 degrees and 197 degrees agreed with the simulated K semimeridia at 75 degrees and 193 degrees in this example. Note that the unreliable semi-Ring.#.K_1 values for rings 15 to 17 had a minimal impact on the hemidivisional CorT because of the very small proportion of valid points in each semi-ring compared to the half cornea that CorT takes into account. This feature provided greater consistency with individual CorT values than the other individual measures.

Figure 5 shows the spherocylindrical fits to the corneal power data for the 2 hemidivisions. Note the division meridian is at 134 degrees and 314 degrees.

Table 7. Ring.#.K and hemidivisional Ring.#.K values corresponding to Figure 4. The hemidivisional Ring.#.K semimeridia started out separated by about 180 degrees for ring 0 (see values marked with * in table); however, this separation decreased with increasing ring number, until there was a separation of only 94 degrees for ring 12 (see values marked with † in table).

		Ring.#.K		Semi-Ring.#.K_1		Semi-Ring.#.K_2	
Ring	Proportion of Valid Measurements	Astig Power (D)	Steep Meridian (Degrees)	Astig Power (D)	Steep Semimeridian (Degrees)	Cyl Power (D)	Steep Semimeridian (Degrees)
0	1.00	0.56	42.6	0.64	41.1*	0.50	224.5*
1	1.00	0.46	41.7	0.61	40.9	0.32	223.2
2	1.00	0.50	41.0	0.70	45.3	0.33	211.8
3	1.00	0.48	41.3	0.65	53.6	0.47	203.7
4	1.00	0.47	51.1	0.75	64.8	0.44	205.5
5	1.00	0.40	51.7	0.68	68.6	0.44	202.1
6	1.00	0.46	54.2	0.89	69.6	0.48	198.1
7	**1.00**	**0.42**	**58.8**	**1.02**	**74.6**	**0.53**	**192.5**
8	1.00	0.40	62.6	1.12	77.5	0.58	189.2
9	0.97	0.39	65.8	1.26	78.6	0.53	186.8
10	0.86	0.14	60.2	1.64	78.6	0.50	183.7
11	0.79	0.07	66.2	1.92	79.2	0.46	182.8
12	0.76	0.12	69.1	1.86	79.3†	0.30	173.6†
13	0.76	0.17	83.3	1.97	84.5	0.38	179.0
14	0.72	0.31	47.2	0.61	87.4	0.78	190.6
15	0.71	0.26	66.8	1.87	334.3	0.95	196.4
16	0.60	0.70	46.1	4.02	81.1	0.95	192.7
17	0.49	0.96	44.6	1.29	71.8	1.13	196.6
18	0.39	1.16	18.2	—	—	1.16	198.2
19	0.38	1.20	17.2	—	—	1.20	197.2
20	0.37	1.30	19.9	—	—	1.30	199.9
21	0.32	1.14	18.5	—	—	1.14	198.5
CorT	—	0.40	44.2	0.94	74.4	0.54	196.7

Astig = astigmatism; CorT = corneal topographic astigmatism

DISCUSSION

Computer-assisted videokeratography provides multiple concentric Placido rings, most of which currently do not contribute to quantifying corneal astigmatism as displayed on simulated K. The combination of the astigmatism values from the majority of Placido rings enables the derivation of a value (CorT) that is more representative of the whole cornea by its closer correlation to the manifest refractive cylinder than using parameters derived from manual K, simulated K from the 3.0 mm zone alone, or corneal wavefront. Figure 4 shows that CorT having the smallest variability of the ORA compared with other measures of corneal astigmatism which include manual K, simulated K, CorW, and PCM ($P < .05$ in all cases, Table 3).

Furthermore, the mean ORA magnitude for CorT was significantly the smallest compared with the 3 other corneal parameters, which reinforces that corneal astigmatism as quantified using CorT matches the manifest refractive cylinder closer in magnitude and orientation than the other measures of corneal astigmatism, as shown in Tables 3 through 6. Note that the raw data in Table 6 of the difference between the mean CorT magnitude and the mean refractive cylinder magnitude is significantly lower than the other 3 corneal astigmatism measures, which is consistent with ORA magnitude and the SD of the ORA being lowest using CorT, which also incorporate meridian values. These key findings reinforce the premise that CorT is an accurate representation of corneal astigmatism when manifest refractive cylinder is the benchmark for assessing the overall astigmatism in the eye.

Manifest refractive cylinder is measured in 0.25 D steps and involves rounding to the nearest lowest step. However, all measures of corneal astigmatism we refer to here are consistently compared with the same manifest refractive cylinder at the corneal plane. Ultimately, it is the manifest refraction that is used as the benchmark in prescribing spectacles and performing excimer laser surgery and, in some cases, in post-incisional surgery.

The method described of calculating CorT with its comprehensive vectorial inclusion of ring data provides additional safety and accuracy in assessing the suitability of patients for corneal astigmatic surgery, including excimer laser surgery, because it is based on multiple data points of the whole cornea, lessening the impact of any single outlier, whatever its cause. In any case, when the ORA may be significant, the treatment paradigm can be adjusted to combine the corneal astigmatism into the refractive treatment plan when performing corneal surgery with the technique of vector planning.[3, 8–10,15–17] Clinical studies involving excimer laser treatment are required to reinforce the CorT findings presented in this paper.

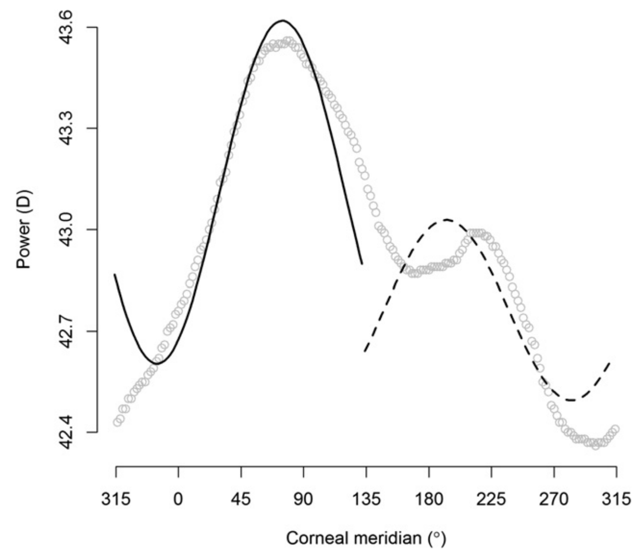

Figure 5. Spherocylindrical fits to corneal power data divided into hemidivisions. The division meridian is at 134 and 314 degrees. Open circles are data, the continuous line is the superior hemidivision spherocylindrical fit (1.02 D @ 74.6, ring no.7, Table 7) and the dashed line is the inferior hemidivision spherocylindrical fit (0.53 D @ 192.5, ring no. 7, Table 7).

The general concept of including the measured axial power across a larger range than a single ring to derive a measure of corneal astigmatism was suggested previously by Maloney et al.,[18] who described a different corneal measure as represented by a spherocylindrical fit of a single contact lens in the central 4.0 mm zone (equivalent to being across several rings 0 to 7 and not individual rings, as in the technique described here). Their justification for choosing this region was to limit the corneal contribution to a central area matching a nominal pupil with a diameter of 4.0 mm. Our results show that using corneal astigmatism values derived from a broader diameter acquisition area, the axial power data correspond well to manifest refractive cylinder. The large SD of the ORAs of the innermost rings (rings 0 to 1, Figure 4) may reflect the sensitivity of these Ring.#.K to misalignment between the visual axis and the corneal apex; here, a large misalignment may lead to an unreliable Ring.#.K because the mismatch between the raw data and the spherocylindrical fit is relatively large compared with other regions of the cornea. This implies that the central scotoma inherently present in many videokeratographs may not reduce the effectiveness of the videokeratograph in measuring overall corneal astigmatic power accurately. The large SD of the ORAs of the outermost rings (rings 14 and higher, Figure 4) is probably caused by loss of data due to the eyelids and distortion of the Placido ring images due to the eyelashes and tear film at the lid margins.

We have performed preliminary investigations into using various weightings for different rings. We implemented the BFGS method of nonlinear optimization (Broyden-Fletcher-Goldfarb-Shanno) with box constraints, which singled out arbitrary rings and gave them a large weighting, while other adjacent rings were allocated a weighting near zero. This is an artifact caused by the large amount of similarity between the Ring.#.Ks of neighboring rings, leading to degeneracy in the optimization. We consider that weightings for calculating CorT are unstable across different eyes for 2 reasons. First, a specific ring measures a different part of the cornea on a flat cornea compared with a steep cornea. Second, local irregularities are likely to invalidate individual Ring.#.Ks, but not all Ring.#.Ks. Therefore, we advise caution when determining individual ring weightings.

In our sample data, we restricted ourselves to virgin astigmatic eyes. Holladay et al.[19] have discussed the shortfalls of estimating corneal axial power from front corneal surface shape after corneal refractive surgery and recommend accounting for the effect of the surgery on the power of the back corneal surface. However, they too were confronted with the problem of selecting an appropriate region of the cornea to use and chose to find the "optimal sample zone diameter that yielded the best correlation with equivalent K reading." Here, we suggest that the postoperative manifest refraction and the corneal plane refractive cylinder value can be used as an alternative to the equivalent K reading. A method similar to that described in this paper can also be applied to the corrected axial power measurements measured via Scheimpflug imaging to find an appropriate corneal zone that best matches the postoperative manifest refractive cylinder.

One benefit of using CorT is that the resulting ORA magnitude is lower than that produced by using alternative corneal measures of manual K, simulated K, CorW, and PCM astigmatism. This may indicate that estimates of ORA are commonly larger than should normally prevail because these 3 other measures of corneal astigmatism do not consistently represent the corneal astigmatism that is actually perceived across wider regions of the cornea. However, even when using CorT with the manifest refractive cylinder, there is still the prevailing occurrence of outlying eyes that have larger ORA magnitudes than desirable. Magnitudes above 1.00 D may limit the acceptable outcome achievable in correcting astigmatism[1] using refractive parameters alone. For this reason, the surgeon may decide not to treat an eye, treat spherical equivalent only, or to use vector planning where corneal and refractive parameters are combined and treat the existing astigmatism to optimize and maximally reduce the resultant amount of corneal astigmatism remaining in such cases[1,3,8–10,15–17] while avoiding potentially unsatisfactory outcomes.[20,A] This technique of combining corneal and refractive parameters has potential for improving outcomes of astigmatism treatments for wider adoption in the future.[21,B] Patients with high ORA amounts can be counseled before surgery that expectations for a complete correction of their existing spherocylindrical refractive error may have to be lowered to realistic levels.

Vector summation of multiple astigmatism ring K values obtained from Placido rings for each hemidivision reduces the singular effect of any aberrant measurement, whether it be an artifactual or actual outlier. Such outliers might be expected from an automated measurement process, such as computer-assisted videokeratography.

Knowledge of whole-of-cornea and hemidivisional astigmatism values can lead to greater consistency in corneal astigmatism outcomes. The derived hemidivisional values can also be used to calculate the TD of the cornea for standardized measures of corneal irregularity across topographers for which assessment of irregularity commonly differ. Treatments that might include corneal parameters for the whole cornea or each hemidivision can rely on guidance from parameters, such as CorT, that have less variability than are currently clinically available. This provides an opportunity to further improve overall visual outcome quality in the routine laser vision correction process.

In conclusion, we describe a new method of quantifying corneal astigmatism, termed CorT, that corresponds well to manifest refractive cylinder which quantifies the total refractive cylinder of the eye including any cerebral processing. When compared based on the range of the ORA magnitude across many eyes, the standard deviation of these magnitudes and the mean difference between corneal and refractive astigmatism values show that CorT aligns significantly more favorably with manifest refractive cylinder than the 4 other commonly used measures of corneal astigmatism; that is, manual K, simulated K, CorW, and PCM. We also describe a consistent way of generating 2 hemidivisional CorT values for a cornea to allow the astigmatism of the cornea to be considered separately for the 2 hemidivisions and for the whole cornea when the 2 are summated. These 2 hemidivisional CorT values allow us to derive a value for the TD, a vectorial measure of corneal irregularity, which when the 2 are summated provide a precise representation of the whole cornea (CorT). Corneal topographic astigmatism, ORA, and TD can be used in the decision-making and consent process as fundamental preoperative parameters to help the surgeon achieve a positive visual outcome when assessing corneal astigmatic parameters for surgery.

WHAT WAS KNOWN

- The simulated K and manual K values measure the corneal astigmatism at the 3.0 mm zone. Corneal wavefront and paraxial curvature matching also measure a limited area of the cornea, resulting in variability when compared with existing manifest refractive cylinder.
- Corneal irregularity is quantified by several topographers with varied parameters that are not directly comparable to each other.

WHAT THIS PAPER ADDS

- When compared to the manifest refraction cylinder, CorT was found to be a better measure of corneal astigmatism than simulated K, manual K, corneal wavefront, or paraxial curvature matching because it is based on more data from a wider area of the cornea.
- Using CorT, a more accurate determination can be established for the amount of astigmatism of the whole cornea or hemidivision of the cornea that requires correcting and the orientation of the incision, ablation, or toric intraocular lens.
- Corneal topographic astigmatism semimeridian values with topographic disparity provide the ability to standardize corneal irregularity assessment between topographers.

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