Corneal Topographic Astigmatism (CorT) to Quantify Total Corneal Astigmatism

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ABSTRACT

PURPOSE: To evaluate the performance of corneal topographic astigmatism (CorT) based on total corneal power measurements.

METHODS: Anterior, posterior, and total corneal power measurements of 526 virgin eyes obtained using the CSO Sirius tomographer (Costuzione Strumenti Oftalmici, Scandicci, Florence, Italy) were analyzed. Individual CorTs were created from each set of data. These CorTs were assessed using ocular residual astigmatism (ORA), which quantifies corneo-refractive differences. A low standard deviation of the ocular residual astigmatism (ORAsd) indicates a low variability between corneal astigmatism and refractive cylinder. A low mean of the ORA magnitude indicates a close correlation of refractive cylinder and corneal astigmatism.

RESULTS: The CorT based on total corneal power measurements had an ORAsd of 0.30 diopters (D) and a mean ORA magnitude of 0.53 D. The CorT candidates based on anterior corneal power measurements all had an ORAsd of at least 0.32 D, and the mean ORA magnitudes were all 0.64 D or greater. Both the ORAsd and mean ORA magnitude of the CorT based on total corneal power measurements were significantly less than those of the CorT based on anterior corneal power measurements (both $P < .001$, as estimated via bootstrapping).

CONCLUSIONS: The CorT based on total corneal power measurements corresponds better, both in variability and closeness, with manifest refractive cylinder than the CorT based on anterior corneal power measurements. This total CorT would be fundamental when planning toric intraocular lenses or limbal relaxing incisions or other corneal astigmatic surgery.

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Over the past two decades, technological innovation has made it possible to measure corneal power with increasing accuracy and detail. Slit scanning,[1] Scheimpflug camera technology,[2] and corneal tomography systems based on ray-tracing principles[3] have provided practitioners with estimates of total corneal power.

Regardless of the ever improving measurements of corneal power, it remains unclear how best to combine the thousands of individual corneal measurements into a single (possibly toric) corneal power measure. It would be useful for this corneal measure to be highly predictive of manifest refractive cylinder, enabling the surgeon to reliably achieve excellent postoperative visual outcomes and maximum reduction of astigmatism where low ocular residual astigmatism (ORA) exists.[4-8] Unfortunately, even the corneal measures currently being generated by state-of-the-art corneal tomographers seem to deviate both systematically and randomly from the manifest refractive cylinder,[9] which represents the total astigmatism of the eye. This phenomenon is unlikely to be entirely resolved due to inherent differences that exist between corneal astigmatism and refractive cylinder.

Alpins et al.[10] previously constructed a corneal power measure, the corneal topographic astigmatism (CorT), that best matches with manifest refractive cylinder in magnitude and orientation. The CorT constructed from anterior corneal power measurements was better than other existing corneal measures (manual keratometry, simulated keratometry, corneal wavefront, and paraxial curvature matching), but still showed the presence of significant random error when compared with manifest refractive cylinder at the corneal plane.

In this study, we investigate whether a CorT constructed from ‘total’ corneal power measurements more closely matches

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manifest refractive cylinder than a CorT constructed from anterior corneal power. We would expect this to be true, because the total corneal power incorporates anterior and posterior corneal curvature information, and thus should be more representative of the complete cornea. Such a parameter would provide greater consistency in quantifying corneal astigmatism magnitude and meridian for corneal assessment and for surgical procedures such as toric implantation, cornea procedures after corneal graft, limbal relaxing incisions, and topography-guided laser procedures.

PATIENTS AND METHODS

STUDY DATA

Refractive and tomographic data were assessed retrospectively for virgin healthy eyes that later proceeded to have refractive laser surgery. Measurements were performed between April 2011 and June 2013. All tomographic data were captured with a CSO Sirius tomographer (Costuzione Strumenti Oftalmici, Scandicci, Florence, Italy), which uses the combination of a Placido disk and a rotating Scheimpflug camera to measure the anterior and posterior corneal surfaces and the corneal thickness across the whole cornea. The exported tomographic data contained ‘equivalent power’ values (referred to here as total power), axial anterior, and posterior power values of each measurement point on the cornea. Measurements were made at 240 points on 30 evenly spaced concentric rings, with diameters ranging from 0.4 to 12.0 mm.

CALCULATIONS

We used the method described by Alpins et al.[10] to derive parameters for total, anterior, and posterior power CorTs. For each measurement type (total, anterior, and posterior CorT), this involved calculating Ring.#.Ks (which are similar to keratometry readings calculated for each ring, with a flat and steep power and steep meridian) and then deriving many CorT candidates by combining Ring.#.Ks from sets of contiguous rings. Because we require CorTs that represent total power instead of curvature, adjustment factors were applied to the anterior and posterior curvature data to turn them into equivalent keratometric power. The adjustment factor for anterior power is the standard adjustment factor normally used to convert from anterior corneal curvature to keratometric power,[11] namely $(1.3375 - 1.0) / (1.376 - 1.0) = 0.90$. The adjustment factor for posterior power is derived similarly, and in our case is $(1.3375 - 1.0) / (1.336 - 1.376) = -8.44$.

The vector difference between the CorT candidates and the manifest refractive cylinder is the ORA.[4] The standard deviation of the ORA magnitudes (ORAsd) is a measure of the variability of the match between the CorT corneal astigmatism and manifest refractive cylinder. The ORAsd allows the CorT candidates to be ranked, where a low ORAsd indicates that a CorT candidate matches the manifest refractive cylinder consistently with minimum variability.

The mean of the ORA magnitudes (ORAmean) is also of clinical relevance. A low ORA magnitude indicates that the CorT is well aligned in meridian and magnitude to the corneal plane manifest refractive cylinder, effectively representing the total refractive power of the eye.

STATISTICAL ANALYSIS

All statistical analyses were performed using the R statistical environment.[12] Parameter estimates, confidence intervals, and *P* values were obtained via simple bootstrapping,[13] using the package ‘boot’[14,15] to generate 1,000 bootstrap samples.

RESULTS

Our results derived from total and anterior corneal power data. We also included results derived from posterior power data for completeness, although these alone were not expected to accurately match refractive measurements.

Five hundred twenty-six virgin healthy eyes were included in the study. Patient age ranged from 20 to 57 years at the time of surgery, and 60% were female.

Figure A (available in the online version of this article) shows the ORAsd and ORAmean estimates for the Ring.#.Ks. For total power, the best individual ring was ring 7 (with a diameter of 2.8 mm); this had an ORAsd of 0.32 diopter (D) and an ORAmean of 0.53 D. The best individual ring for anterior power was also ring 7, with an ORAsd of 0.35 D and an ORAmean of 0.65 D. In contrast, the Ring.#.Ks derived from posterior power data bear far less resemblance to refractive cylinder. The best individual ring derived from posterior power data was ring 18, with an ORAsd of 2.73 D and an ORAmean of 2.64 D. The extremely large values of ORAsd and ORAmean for posterior power data indicate that the adjusted posterior corneal astigmatism did not correspond closely to manifest refractive cylinder, neither in magnitude nor meridian.

Table 1 shows the ORAsd and ORAmean values of total power CorT candidates created from various contiguous ring ranges, and **Table 2** shows the values for the anterior power CorT candidates. In each table, the ring ranges shown were the 10 ring ranges that had the lowest ORAsd values. For the case of total power, there are ring ranges that produced both a low ORAsd and a low ORAmean. However, in the case of anterior

TABLE 1

CorT ORA Statistics for the 10 Ring Ranges With the Smallest ORAsd Derived From Total Corneal Power[a]

Ring Range	Total Corneal ORAsd (D)	Total Corneal ORAmean (D)
1 to 22	0.295 (0.012)	0.628 (0.013)
5 to 13	0.296 (0.013)	**0.527** (0.013)
2 to 21	0.296 (0.013)	0.616 (0.013)
2 to 22	0.296 (0.012)	0.632 (0.013)
1 to 21	0.296 (0.013)	0.613 (0.013)
5 to 12	0.297 (0.013)	**0.527** (0.013)
1 to 23	0.297 (0.012)	0.643 (0.013)
3 to 17	0.297 (0.015)	0.557 (0.013)
2 to 20	0.297 (0.013)	0.599 (0.013)
5 to 11	0.297 (0.013)	**0.527** (0.013)
6 to 11	0.300 (0.013)	**0.523** (0.013)

CorT = corneal topographic astigmatism; ORA = ocular residual astigmatism; ORAsd = standard deviation of ORA magnitudes; D = diopters; ORAmean = mean of ORA magnitudes

[a] *Rows are sorted according to ORAsd. Entries in brackets are standard errors. The minimum ORAmean value from all ring ranges is 0.523 D, occurring for ring range 6 to 11. ORAmean values that are not statistically significantly different at a 5% confidence level from this minimum are highlighted in bold.*

TABLE 3

CorT ORA Statistics Derived From Total Corneal Power for the Ring Ranges With the Smallest ORA That Also Have a Low ORA Mean Value

Ring Range	Total Corneal ORAsd (D)	Total Corneal ORAmean (D)
5 to 13	0.296 (0.013)	0.527 (0.013)
5 to 12	0.297 (0.013)	0.527 (0.013)
5 to 11	0.297 (0.013)	0.527 (0.013)
4 to 13	0.297 (0.013)	0.536 (0.013)
5 to 14	0.298 (0.015)	0.528 (0.013)
4 to 14	0.299 (0.014)	0.535 (0.013)
5 to 10	0.299 (0.014)	0.529 (0.013)
6 to 13	0.300 (0.014)	0.525 (0.013)
6 to 11	0.300 (0.013)	0.523 (0.013)
5 to 15	0.300 (0.016)	0.531 (0.013)
6 to 10	0.300 (0.014)	0.523 (0.013)
6 to 12	0.301 (0.014)	0.524 (0.013)
6 to 9	0.302 (0.014)	0.527 (0.013)
6 to 14	0.303 (0.015)	0.526 (0.013)

CorT = corneal topographic astigmatism; ORA = ocular residual astigmatism; ORAsd = standard deviation of ORA magnitudes; D = diopters; ORAmean = mean of ORA magnitudes

TABLE 2

CorT ORA Statistics for the 10 Ring Ranges With the Smallest ORAsd Derived From Anterior Corneal Power[a]

Ring Range	Anterior Corneal ORAsd (D)	Anterior Corneal ORAmean (D)
1 to 23	0.318 (0.011)	0.700 (0.014)
2 to 23	0.318 (0.012)	0.703 (0.014)
2 to 22	0.318 (0.012)	0.694 (0.014)
3 to 22	0.319 (0.012)	0.697 (0.014)
1 to 22	0.319 (0.012)	0.692 (0.014)
3 to 23	0.319 (0.011)	0.706 (0.014)
4 to 22	0.320 (0.012)	0.700 (0.014)
1 to 24	0.321 (0.011)	0.713 (0.014)
4 to 23	0.321 (0.012)	0.710 (0.014)
2 to 21	0.321 (0.012)	0.687 (0.014)
4 to 14	0.329 (0.012)	**0.641** (0.014)
5 to 11	0.332 (0.012)	**0.637** (0.015)

CorT = corneal topographic astigmatism; ORA = ocular residual astigmatism; ORAsd = standard deviation of ORA magnitudes; D = diopters; ORAmean = mean of ORA magnitudes

[a] *Rows are sorted according to ORAsd. Entries in brackets are standard errors. The minimum ORAmean value from all ring ranges is 0.637 D, occurring for ring range 5 to 11. ORAmean values that are not statistically significantly different at a 5% confidence level from this minimum are highlighted in bold. The only ring range in the first 40 to have a low ORAmean is from rings 4 to 14.*

power, those ring ranges that produced a low ORAsd did not produce a low ORAmean. The lowest ORAsd and ORAmean values derived from total power data were significantly lower than the lowest ORAsd and ORAmean values derived from anterior power data (for both, $P < .001$). The best ORAsd and ORAmean overall were derived from total power data, with a ring range of 5 to 13 (2.0 to 5.2 mm diameter).

Table 3 presents those total power CorT candidates with the lowest ORAsd values that also had a low ORAmean value (**Table 1**). There were no statistically significant differences at the 5% confidence level between these candidates with respect to ORAsd or ORAmean. By focusing our attention on the ring ranges of these total power CorT candidates, we observed that all of them describe roughly the same part of the cornea, namely the annulus with an inner diameter of 2 mm and an outer diameter of somewhere between 4 and 6 mm.

DISCUSSION

Total corneal power measurements (incorporating anterior and posterior cornea) allowed us to calculate a better CorT than was possible with anterior corneal power measurements alone, with a lower variability and lower mean magnitude of the ORA, and a better correspondence between low ORA variability and low ORA mean.

Our anterior CorT measure was derived from axial curvature data because our intention was to make it comparable with simulated keratometry; our experience indicates that simulated keratometry values from several topographers were calculated on the basis of axial curvature. An advantage of using axial curvature data instead of tangential curvature data was that the resulting corneal measure should be compatible with existing formulas used to calculate intraocular lens power, using existing lens constants.

The axial curvature data were converted using the standardized keratometric index of refraction ($n = 1.3375$). This attempts to account for the negative power of the posterior corneal surface by setting it to a fixed proportion of the power of the anterior surface. Assuming that the refractive index of the cornea is 1.376, this proportion works out to be $(1 - ((1.3375 - 1) / (1.376 - 1))) = 0.102$. Recently, Koch et al.[16] found corneas with a with-the-rule anterior corneal surface that the amount of astigmatism on the posterior cornea ($\text{Astig}_{\text{Post}}$) was related to the amount of astigmatism on the anterior cornea ($\text{Astig}_{\text{Ant}}$) by the following rule: $\text{Astig}_{\text{Post}} = 0.101\ \text{Astig}_{\text{Ant}} + 0.221$. This indicates that the amount of astigmatism contributed by the posterior cornea was being underestimated by approximately 0.22 D when the standardized keratometric index of refraction is used. In our results, we found that the ORA mean was 0.17 D lower when derived from total CorT (ORA mean = 0.53 D) than when derived from anterior CorT (ORAmean = 0.70 D). This difference of 0.17 D is close to the 0.22 D found by Koch et al., which confirms that the total CorT measure behaved as expected when compared to the anterior CorT. Note that this comparison was valid because 71% of the eyes in our study had with-the-rule anterior corneal astigmatism (defined as 60° to 120°[16]), 14% had oblique anterior corneal astigmatism, 13% had less than 1 D of against-the-rule anterior corneal astigmatism (0° to 30° and 150° to 180°[16]), and only 2% had more than 1 D of against-the-rule anterior astigmatism.

Recently, there has been a suggestion that posterior corneal astigmatism should account for all of the ORA, and that any difference that we are seeing is due to measurement error.[9] The opinion that corneal measurements and refractive measurements only differ because of imprecise measurement is not new, although it was previously discussed using different terms.[17,18] In our data, the amount of systematic mismatch between the total CorT and the manifest refractive cylinder is 0.52 D. Although this is significantly less than for other corneal measures, it is still not zero. This supports the longstanding view that manifest refractive cylinder is not just caused by corneal astigmatism, even when the contribution of the posterior corneal surface is taken into account. Non-corneal contributors likely to manifest refractive cylinder include lenticular astigmatism and processing in the visual cortex.[4,19] Also, refractive measurements are aligned to the center of the pupil, whereas corneal astigmatism measurements are centered on the corneal apex, which may also lead to a variable mismatch.

A corneal measure that is consistently associated with a lower ORA is easier to use during surgery planning, because the surgeon will be faced with fewer cases of patients with problematically high levels of ORA and less likelihood of adverse visual outcomes.[5,7,8] Furthermore, a routine calculation of ORA preoperatively can indicate suitability of the patient to the surgeon. For example, a high ORA would forewarn the surgeon of the need to advise the patient of remaining astigmatism postoperatively, reduce patient expectations regardless of how perfect the procedure was, or identify the patient as not suitable for laser vision correction.

It is not the intention of this study to measure the lenticular astigmatism, nor would it influence the outcomes or conclusions because the lenticular astigmatism is consistently included in all groups examined.

The adjusted posterior corneal power measurements did not match manifest refractive cylinder closely at all, in neither magnitude nor orientation. This is consistent with recent research by Koch et al.,[16] which showed that the steep posterior corneal meridian tended to be aligned closer to, but not necessarily coinciding with, the vertical 90° meridian.

Recently, Koch et al.[9] introduced the 'Baylor toric intraocular lens nomogram' to adjust the results of anterior-surface corneal topographers for the effect of the posterior cornea. Such an adjustment is an important contribution that allows surgeons to address the systematic mismatch between the anterior corneal measurement and the manifest refraction. However, the simplistic nature of the nomogram adjustment means that it cannot reduce any variability that occurs in individual cases. Thus, the variability of the ORA magnitude derived from the total power CorT will still be lower than the variability of the ORA magnitude derived from anterior corneal measurements adjusted with the Baylor nomogram.

For this study, we used actual corneal curvature data, as opposed to converted tomographer power data. The actual corneal curvature data has not previously been available to users of corneal tomographers other than the CSO Sirius and the Ziemer Galilei (Ziemer Ophthalmic Systems, Port, Switzerland). Further studies are underway to examine total CorT with other tomographers as data become available. Hence, it will be possible to generate CorT total corneal power measures that perform similarly across different tomographers, providing consistency in the measurements necessary for accurate surgical astigmatic planning and management.

In a study that introduced the CorT,[10] the concept of hemidivisional CorTs was also introduced to allow for the characterization of irregular corneas. Here, the cornea was divided conceptually into two hemidivisions, with each hemidivision having its own separately generated CorT. The two hemidivisional CorTs can be combined via a summated vector mean to generate the whole-of-cornea CorT. Because of the close link between the hemidivisional CorTs and whole corneal CorT, we would expect that hemidivisional CorTs based on total corneal power would better represent the refractive power of the cornea than hemidivisional CorTs based on anterior corneal power only. However, validation of hemidivisional CorTs is outside the scope of this article.

Obtaining an accurate parameter for the total astigmatic power of the cornea and its meridian is of utmost importance—whether it be in selecting and orienting toric IOLs, the length and placement of limbal relaxing incisions, astigmatism postoperative corneal graft, or the treatment of refractive astigmatism using excimer laser where corneal parameters are included in treatment planning.[4] The CorT based on total corneal power is a measure of astigmatism that can be used for regular and irregular corneas. We have shown that the CorT derived from total corneal power measurements better matches manifest refractive cylinder than the CorT derived from anterior corneal power measurements. This means that it also outperforms simulated keratometry, manual keratometry, corneal wavefront, and paraxial curvature matching.[10] Because the CorT is calculated on an individual basis without the use of nomograms, it inherently outperforms corneal astigmatism measures that have been corrected by using population-based nomogram adjustments.

AUTHOR CONTRIBUTIONS

Study concept and design (NA, JKYO); data collection (NA, JKYO, GS); analysis and interpretation of data (NA, JKYO, GS); drafting of the manuscript (NA, JKYO, GS); critical revision of the manuscript (NA, JKYO, GS); statistical expertise (JKYO)

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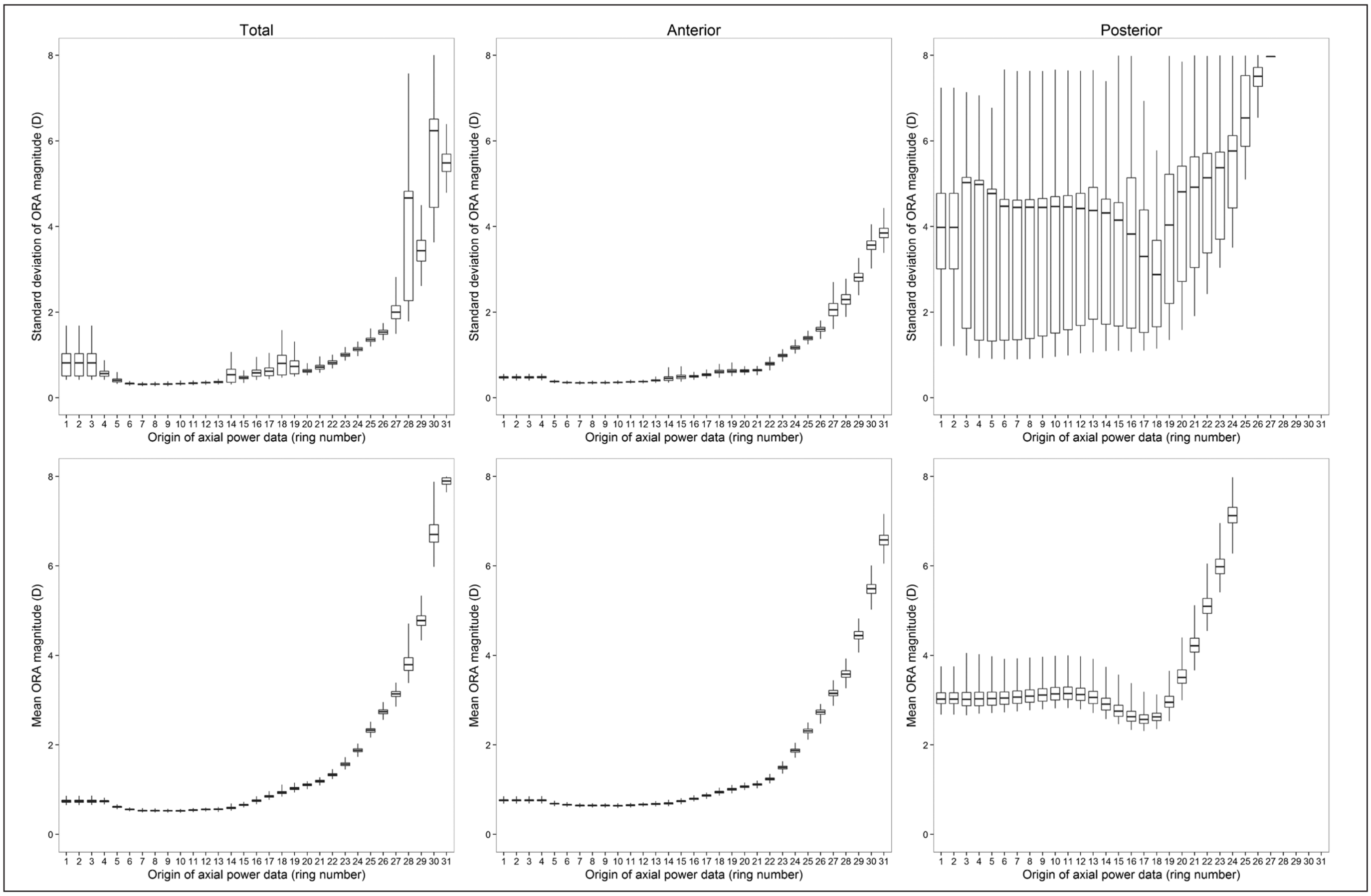

Figure A. Standard deviation and mean of the ocular residual astigmatism (ORA) magnitude for various Ring.#.Ks, as derived from total, anterior, and posterior corneal power measurements.