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Corneal Topographic Astigmatism Based on Total Corneal Power Data (CorT Total): A Benchmark for Total Corneal Astigmatism

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Purpose: To evaluate how closely manufacturer-provided measures of total corneal astigmatism correspond with the manifest refractive cylinder, as compared to a benchmark of corneal topographic astigmatism calculated on the basis of measured total corneal power (TCP) data (CorT Total).

Methods: The SD of the ocular residual astigmatism magnitude (ORAsd) was evaluated for normal virgin eyes based on an optimized benchmark CorT Total and the various measures of total corneal astigmatism provided by 3 different Scheimpflug tomographers.

Results: The CorT Total corresponded with the manifest refractive cylinder at least as well as all the measures of total corneal astigmatism provided by the tomographers [Sirius CorT Total ORAsd: 0.320D (standard error [SE] 0.017D), Sirius TCP 4 mm ORAsd: 0.324D (SE 0.017D); Pentacam CorT Total ORAsd: 0.338D (SE 0.027D), Pentacam total corneal refractive power apex zone 4 mm ORAsd: 0.337D (SE 0.029D); Galilei CorT Total ORAsd: 0.472D (SE 0.068D), and Galilei TCP2 ORAsd: 0.536D (SE 0.124D)]. The difference between CorT Total and best measure on each tomographer was not statistically significant (Sirius TCP 4 mm: $P = 0.24$, Pentacam total corneal refractive power apex zone 4 mm: $P = 0.64$, Galilei TCP2: $P = 0.24$). Most of the manufacturer-provided measures did not correspond closely with the manifest refractive cylinder. When there were multiple measures of total corneal astigmatism, those derived from a zone with a diameter of 4.0 mm corresponded best with the manifest refractive cylinder.

Conclusions: The CorT Total is a reliable benchmark measure that can be used to assess how well other measures of total corneal astigmatism correspond with the manifest refractive cylinder.

Key Words: corneal topographic astigmatism (CorT), corneal tomography, total corneal power

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Corneal tomography allows a clinician to image the cornea in 3 dimensions and thus provides information about the curvatures and relative positions of the anterior and posterior corneal surfaces. Corneal tomographers commonly use some variant of ray tracing to calculate local measures of corneal power at many positions on the cornea,[1–4] and these can be displayed as total corneal power (TCP) maps. In addition, summary values that are referred to as "total corneal power" (TCP) or "total corneal refractive power" (TCRP) are often provided, which can be used in a similar way to simulated keratometry values during surgical planning for astigmatism procedures.[5,6]

Unfortunately, it has been unclear whether tomographic corneal astigmatism measurements can be used directly when planning for refractive surgery because their relationship to the manifest refractive cylinder remains enigmatic. A recent study by Wallerstein et al[7] indicates that corneal astigmatism measurements should not be used in the planning of LASIK treatments without an understanding of their relationship to the manifest refractive cylinder.

In addition, some tomographers provide multiple measures of TCP, calculated from different zones of the cornea, and it is left to the discretion of the surgeon to decide which measure to use. There has been little recent evidence-based guidance about which of these measures is best suited for surgical planning where corneal values are required.[8] Earlier results were based on scanning-slit technology.[4,9,10] However, the scanning-slit imaging technique differs[11,12] from the Scheimpflug imaging technique used by most current corneal tomographers, so it is not clear that conclusions based on scanning-slit imaging can be extrapolated to Scheimpflug imaging.

In this study, we determine which of the multiple tomographer-generated measures of TCP correspond well with the manifest refractive cylinder at the corneal plane. We also assess whether corneal topographic astigmatism derived from TCP measurements (CorT Total)[13] can be used as

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a cross-tomographer benchmark to assess tomographer-generated measures of TCP.

MATERIALS AND METHODS

This retrospective multicenter study was performed in compliance with the tenets of the Declaration of Helsinki and was approved by the Melbourne Excimer Laser Group Protocol and Ethics Committee.

CorT Rationale

The main factors that contribute to the manifest refractive cylinder are corneal astigmatism, noncorneal astigmatism (lenticular astigmatism, perceptual adaptation), and refractive measurement error. This can be written as:

$$\begin{aligned}\text{manifest refractive cylinder} = {} & \text{corneal astigmatism} \\ & + \text{noncorneal astigmatism} \\ & + \text{refractive measurement} \\ & \quad \text{error}\end{aligned}$$

To be precise, the "manifest refractive cylinder" term is the cylindrical component of a subjective refraction at the corneal plane, the "corneal astigmatism" term is the component of the subjective refractive cylinder due to the cornea, and the "noncorneal astigmatism" term encompasses the effect of noncorneal factors (lenticular astigmatism and perceptual adaptation) on the subjective refractive cylinder. The "refractive measurement error" term includes the possibility of incorrect or ambiguous refractive results and the discretized steplike nature of manifest refractive values.

The term "corneal astigmatism," which quantifies the effect of the cornea on the subjective refractive cylinder, is exactly what is required during surgical planning when the postoperative refractive outcome is important. In reality, such a quantity is dependent not only on the cornea but also on other optical factors such as the pupil size and shape. None of the devices that measure corneal astigmatism can produce a measurement that matches the term in the formula exactly because they produce objective, not subjective, measurements. Indeed, some devices produce multiple measures of corneal astigmatism based on simulated pupils of differing sizes or on specific annular regions of the cornea. Because of this, it makes sense to divide the "corneal astigmatism" term into 2 separate terms, namely the actual measurement and the measurement error. Thus, the overall formula becomes:

$$\begin{aligned}\text{manifest refractive cylinder} = {} & \text{measured corneal astigmatism} \\ & + \text{corneal measurement error} \\ & + \text{noncorneal astigmatism} \\ & + \text{refractive measurement} \\ & \quad \text{error}\end{aligned}$$

After the measured corneal astigmatism term is subtracted from both sides, the left hand side becomes the difference between measured refractive cylinder and measured corneal astigmatism, which is also known as ocular residual astigmatism (ORA):[14]

$$\begin{aligned}\text{ORA} = {} & \text{corneal measurement error} \\ & + \text{noncorneal astigmatism} \\ & + \text{refractive measurement error}\end{aligned}$$

The right hand side of this equation can be adopted as a statistical model. In such a model, under the reasonable assumption that corneal measurement error is independent of noncorneal astigmatism and refractive measurement error, the total variance can be partitioned[15] into 2 parts, one of which can be attributed to corneal measurement error:

$$\begin{aligned}\text{var (ORA)} = {} & \text{var (corneal measurement error)} \\ & + \text{var (noncorneal astigmatism} \\ & + \text{refractive measurement error)}\end{aligned}$$

For any existing set of refractive measurements, noncorneal astigmatism and refractive measurement error have a fixed (although unknown) variance because each eye that was measured had existing values of manifest and noncorneal astigmatism when the corneal measurement was performed, independent of how corneal astigmatism was measured. This means that the variance of ORA can be used as a proxy for the variance of corneal measurement error as we vary the method of measuring corneal astigmatism. Thus, we should prefer corneal measures of astigmatism where the variance of ORA is low because this implies that corneal measurement error is a less important predictor in the model.

The CorT is a corneal measure of astigmatism that is constructed to have a low *SD of the ORA magnitude* (ORAsd), which means that the variance of ORA will also be low. The CorT based on TCP measurements (CorT Total) has been shown to have a lower ORAsd than manual keratometry, simulated keratometry, and a CorT based on anterior corneal power measurements. Thus, we already expect the CorT Total to correspond closely with the manifest refractive cylinder.[13]

In this study, we use the ORAsd of an optimized CorT Total, which is theoretically close to minimal, as a benchmark to assess the ORAsds of the tomographer-generated corneal astigmatism measures.

Study Data

All eyes included were healthy virgin eyes with no previous surgery and no cataract, amblyopia, keratoconus or keratoconic indications, or other preexisting ocular conditions.

Patients came from a number of different populations: 1) A clinic in Melbourne, Australia, provided patient data measured between April 2011 and December 2014 with the Sirius tomographer (Costruzione Strumenti Oftalmici, Florence, Italy), which uses a Scheimpflug camera combined with Placido corneal topography. 2) Three separate clinics provided patient data measured with the Pentacam HR tomographer (Oculus Optikgeräte GmbH, Wetzlar, Germany), which uses a Scheimpflug camera. The first clinic in Atlanta, GA, supplied data collected between October 2006 and 2016. The second clinic in Los Angeles, CA, supplied data collected between October 2016 and April 2017. The third clinic in Melbourne, Australia, supplied data collected between January 2014 and February 2017. 3) A clinic in Philadelphia, provided patient data measured between January 2013 and April 2014 with the Galilei G4 tomographer (Ziemer Ophthalmic Systems AG, Zurich, Switzerland), which uses a dual Scheimpflug camera system combined with Placido corneal topography.

All data collected with the Pentacam were reprocessed by technical personnel at Oculus between December 2016 and August 2017 to ensure that all processing was performed with the most up-to-date version of the tomography software possible. Data were filtered to retain only measurements in which the capture quality was considered to be good and the machine calibration status was valid.

For each eye included in the study, the most recent tomographic measurement was selected if there were multiple provided. For each selected measurement, TCP values across the whole cornea were exported: on the Sirius (v3.2.1.20), they are called "refractive equivalent power;" on the Pentacam (v1.20b39), they are called "total corneal refractive power;" and on the Galilei (v6.0.3), they are called "total corneal power." The Sirius and Galilei export these data as concentric rings in polar form, whereas the Pentacam exports data as a regular grid in Cartesian form. In all cases, the exported data are centered on the corneal vertex normal, which is also the position of the first Purkinje image. This position has also sometimes been called the "corneal apex"[8,16] although this can be misleading because the term "corneal apex" can also refer to the point of maximum curvature or to the most anterior point on the cornea. In the rest of this study, all references to the "corneal apex" (often used in conjunction with results from the Pentacam) refer to the corneal vertex normal.

The exported TCP values for each eye were used to calculate an optimized CorT Total following the procedure previously detailed by Alpins et al.[13,17] For this study, all calculations were performed in the R statistical environment[18] using custom software. The procedure begins by determining which annular region should be used to derive the CorT Total for each tomographer. This involved calculating Ring.#.Ks (similar to keratometry readings) for narrow annular regions of the cornea and then using a global search of all possible ring ranges to find the combination of Ring.#.Ks (which equates to a wide annular region) that minimized the SD of the ORAsd[14] over all eyes measured with that tomographer. The ORAsd is used as the key measure because it measures the variability of the double angle vector difference between a measure of corneal astigmatism and the manifest refractive cylinder at the corneal plane. A low ORAsd indicates low variability, and thus indicates that the measure of corneal astigmatism correlates well with the manifest refractive cylinder. After an appropriate annular region had been selected for each tomographer, this region was used consistently across all eyes measured with this tomographer type. CorT Total was calculated for each eye as a summated vector mean, weighted by the proportion of valid measurements per ring[17] to reduce the influence of missing data. Note that because the CorT Total ring ranges were optimized on these data sets, the resulting ORAsds in this study should be seen as a benchmark, as opposed to a quantification of the real-world performance of the CorT Total.

For each total corneal astigmatism measure, we evaluated summary statistics for ORA, namely SD (ORAsd) and mean (ORAmean). The ORAsd is a measure of how well the corneal astigmatism measure correlates with the manifest refractive cylinder, with a low ORAsd indicating a better correlation. The ORAmean is a measure of how much systematic difference there is between corneal astigmatism measure and manifest refractive cylinder. The ORAmean is expected to be nonzero because of noncorneal contributions to the manifest refractive cylinder. However, with all other factors (including ORAsd) being equal, a low ORAmean is preferred to a high ORAmean because this reduces the impact of ORA on the surgical planning process and allows a surgeon to select a treatment that is closer to the safe default of the manifest refractive cylinder.

In addition to the raw TCP values across the cornea, summary total corneal astigmatism values were exported: on the Sirius, these were exported for diameters of 3.0, 3.5, 4.0, 4.5, and 5.0 mm centered on corneal apex; on the Pentacam, the 4 types "TCRP apex zone," "TCRP apex ring," "TCRP pupil zone," and "TCRP pupil ring" were exported for diameters of 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, and 8.0 mm; and on the Galilei, "Total Corneal Power 1 (Ray Traced)" and "Total Corneal Power 2 (Ray Traced)" were exported (based on data from the entire cornea, potentially out to a diameter of 10 mm if the data was deemed to be reliable). To determine how well the exported total corneal astigmatism values matched the manifest refractive cylinder, ORAsds were calculated for each type of exported measure.

All statistical analysis was performed by bootstrapping[19] using the boot package[20] with 1000 bootstrap estimates in the R statistical environment.[18] This includes standard errors of ORAsd estimates and P values of comparisons of ORAsds.

RESULTS

The study included 993 eyes in total, including 606 eyes measured with the Sirius (mean age 34.7 ± 8.4 years, age range 20–57 years, 56% female), 197 eyes measured with the Pentacam (mean age 35.6 ± 10.6 years, age range 12–78 years, 49% female), and 190 eyes measured with the Galilei (mean age 36.9 ± 13.3 years, age range 20–89 years, 58% female). Basic statistics for the refractive and tomographic data for each group are shown in Table 1.

Results for each type of tomographer are shown in separate tables: Sirius in Table 2, Pentacam in Table 3, and Galilei in Table 4.

For all 3 tomographers, the CorT Total did not have a statistically significantly lower ORAsd than the manufacturer-provided measure with the lowest ORAsd (Sirius TCP 4 mm: $P = 0.24$, Pentacam TCRP apex zone 4 mm: $P = 0.64$, Galilei TCP 2: $P = 0.24$). However, many of the other measures provided by each manufacturer had substantially higher values of ORAsd.

TABLE 1. Basic Summary Statistics (All at Corneal Plane in Diopters)

Tomographer	Measurement Type	Min	Mean (SD)	Max
Sirius	Refractive spherical equivalent	−9.87	−3.46 (1.92)	+0.38
	Refractive cylinder magnitude	0.00	0.65 (0.70)	5.00
	Mean simulated keratometry	40.02	43.72 (1.30)	47.61
	TCP astigmatism (4.0 mm)	0.02	0.77 (0.56)	3.68
Pentacam	Refractive spherical equivalent	−11.73	−3.27 (2.40)	+4.49
	Refractive cylinder magnitude	0.00	0.69 (0.94)	6.25
	Mean simulated keratometry	39.15	43.22 (1.36)	47.35
	TCP astigmatism (4.0 mm apex zone)	0.1	0.97 (0.76)	4.8
Galilei	Refractive spherical equivalent	−12.81	−2.99 (3.12)	+6.49
	Refractive cylinder magnitude	0.00	0.94 (0.88)	4.18
	Mean simulated keratometry	40.35	44.16 (1.58)	49.03
	TCP astigmatism (TCP 2)	0.05	0.99 (0.80)	4.70

In a comparison of different measure types on the Pentacam (see Table 2), regions centered on the corneal apex tended to have lower ORAsd values than those centered on the pupil center. Ring regions tended to have low ORAsds for a diameter of 3 mm, whereas zone regions tended to have low ORAsds for a diameter of 4 mm.

DISCUSSION

In this study, we have shown that an optimized CorT Total corresponds with the manifest refractive cylinder at least as well as all measures of total corneal astigmatism currently calculated by the tomographic software on the 3 tomographers used in this study. We suggest that an optimized CorT Total can be used as a reliable benchmark for total corneal astigmatism.

TABLE 2. ORA Results of the Sirius (n = 606 Eyes)

Measurement Type	ORAsd (SE)*	ORAmean (SE)*
CorT total (0.9–2.7 mm radius)	**0.320** (0.017)†	**0.512** (0.013)†
TCP 3.0 mm	0.411 (0.041)	0.566 (0.017)
TCP 3.5 mm	0.330 (0.017)	0.537 (0.014)
TCP 4.0 mm	**0.324** (0.017)†	**0.528** (0.013)†
TCP 4.5 mm	0.380 (0.034)	0.536 (0.015)
TCP 5.0 mm	0.383 (0.030)	0.540 (0.016)

*ORAsd and ORAmean values shown are bootstrap estimates (with SEs in brackets).

†For each type of total corneal astigmatism measure, the measure with the lowest ORAsd is shown in bold.

SE, standard error.

Both Sirius and Pentacam can calculate many different measures of total corneal astigmatism based on varying regions of the cornea. Our assessment of the manufacturer-provided measures of total corneal astigmatism suggests that a measure calculated from a zone of diameter 4.0 mm centered at the corneal apex provides the best correspondence with the manifest refractive cylinder of all the total corneal astigmatism measures tested. On the Pentacam, corneal astigmatism measures based on narrow annular "ring" regions performed worse than full zone regions. In addition, measures centered at the pupil center performed worse than those centered at the corneal apex. These results concerning centration are consistent with the outcomes of various studies that have shown parity[21–23] or improvement[24–27] of the postoperative spherical equivalent and higher-order aberrations when corneal ablations are centered on the corneal apex as opposed to the pupil center.

Savini et al[8] evaluated the ability of the spherical equivalent of various TCRPs (2.0, 3.0, and 4.0 mm apex zones and 2.0, 3.0, and 4.0 apex rings) produced by the Pentacam to predict the refractive change due to myopic excimer laser surgery. They found that the 3.0 mm apex zone and the 2.0 mm apex ring TCRP measurements performed the best but suggested that their methodology might be sensitive to the aspheric ablation profile used by the excimer laser. In another study, Savini et al[16] evaluated the performance of the spherical equivalent of various TCRPs (2.0 and 3.0 mm apex zones and 2.0 and 3.0 mm apex rings) in the calculation of intraocular lens power and found no statistically significant differences between the different measures. Part of the problem with assessing the different measures in their study was that the results differed depending on the particular formula used to calculate intraocular lens power. Similar studies of "total optical power" generated by slit-scanning imaging[4,9,10] showed that a 4.0 mm zone should be used for calculating the power of intraocular lenses, whereas a study with an optical coherence tomographer[28] found that the TCP should be calculated from a 3.0 mm zone if it is to track the manifest refraction. All of these studies used indirect methods requiring surgical intervention to evaluate the relationship between TCRP and manifest refraction. By contrast, the current study directly evaluated the astigmatic component of the TCRP against the manifest refractive cylinder in virgin eyes and found that the 4.0 mm apex zone and the 3.0 mm apex ring provide the closest measures to the manifest refractive cylinder.

This study did not directly compare the 3 different tomographers used because each tomographer was used to measure a different population of patients. Indeed, the data set for the Pentacam was derived from 3 distinct populations. Any comparative study of TCP measured using different tomographers would ideally be conducted on a large cohort of patients (we would recommend at least 150 eyes), with multiple tomographic measurements on each patient performed at the same consultation. Such a study has already been carried out comparing the Sirius and the Pentacam,[1] indicating that the 2 show only moderate levels of agreement, but the study could be improved by the use of

TABLE 3. ORA Results of the Pentacam (n = 197 Eyes)

Measurement Type	ORAsd (SE)*	ORAmean (SE)*
CorT total (0.15–2.65 mm radius)	**0.338** (0.027)†	**0.642** (0.025)†
TCRP apex zone 1 mm	0.405 (0.026)	0.695 (0.029)
TCRP apex zone 2 mm	0.381 (0.026)	0.681 (0.028)
TCRP apex zone 3 mm	0.350 (0.026)	0.646 (0.025)
TCRP apex zone 4 mm	**0.337** (0.029)†	**0.633** (0.025)†
TCRP apex zone 5 mm	0.351 (0.032)	0.654 (0.026)
TCRP apex zone 6 mm	0.384 (0.033)	0.684 (0.027)
TCRP apex zone 7 mm	0.412 (0.031)	0.724 (0.029)
TCRP apex zone 8 mm	0.443 (0.027)	0.780 (0.031)
TCRP apex ring 1 mm	0.397 (0.026)	0.720 (0.027)
TCRP apex ring 2 mm	0.354 (0.026)	0.657 (0.025)
TCRP apex ring 3 mm	**0.345** (0.029)†	**0.640** (0.025)†
TCRP apex ring 4 mm	0.415 (0.035)	0.689 (0.030)
TCRP apex ring 5 mm	0.465 (0.039)	0.768 (0.032)
TCRP apex ring 6 mm	0.504 (0.037)	0.844 (0.037)
TCRP apex ring 7 mm	0.574 (0.030)	0.963 (0.042)
TCRP apex ring 8 mm	0.780 (0.061)	1.188 (0.057)
TCRP pupil zone 1 mm	0.624 (0.078)	0.657 (0.047)
TCRP pupil zone 2 mm	0.437 (0.040)	0.631 (0.031)
TCRP pupil zone 3 mm	0.378 (0.031)	0.613 (0.027)
TCRP pupil zone 4 mm	**0.366** (0.030)†	**0.613** (0.027)†
TCRP pupil zone 5 mm	0.371 (0.030)	0.639 (0.027)
TCRP pupil zone 6 mm	0.395 (0.033)	0.677 (0.027)
TCRP pupil zone 7 mm	0.416 (0.032)	0.714 (0.029)
TCRP pupil zone 8 mm	0.438 (0.028)	0.768 (0.032)
TCRP pupil ring 1 mm	0.517 (0.057)	0.681 (0.037)
TCRP pupil ring 2 mm	0.368 (0.028)	0.638 (0.027)
TCRP pupil ring 3 mm	**0.363** (0.031)†	**0.634** (0.025)†
TCRP pupil ring 4 mm	0.425 (0.038)	0.694 (0.031)
TCRP pupil ring 5 mm	0.477 (0.042)	0.766 (0.035)
TCRP pupil ring 6 mm	0.510 (0.037)	0.834 (0.036)
TCRP pupil ring 7 mm	0.557 (0.031)	0.933 (0.040)
TCRP pupil ring 8 mm	0.771 (0.070)	1.167 (0.059)

*ORAsd and ORAmean values shown are bootstrap estimates (with SEs in brackets).

†For each type of total corneal astigmatism measure, the measure with the lowest ORAsd is shown in bold.

SE, standard error.

a true benchmark such as an optimized CorT Total to allow the ranking of the measurements regarding the manifest refraction.

Any measures of TCP that correspond significantly worse than the CorT Total with the manifest refractive cylinder should probably not be used when planning corneal refractive surgery, especially with procedures such as vector planning, because surgically induced changes in such measures will be difficult to relate to refractive outcomes. In addition, the performance of manufacturer-provided measures may change in the future because the methodology underlying them could evolve in future versions of the manufacturer-provided tomography software. A validated fully described benchmark such as the CorT Total can provide a stable basis for understanding the consequences of algorithmic changes in the manufacturer-provided software.

TABLE 4. ORA Results of the Galilei (n = 190 Eyes)

Measurement Type	ORAsd (SE)*	ORAmean (SE)*
CorT total (1.0–2.6 mm radius)	**0.472** (0.068)†	**0.658** (0.035)†
TCP 1	0.544 (0.126)	0.637 (0.041)
TCP 2	**0.536** (0.124)†	**0.631** (0.041)†

*ORAsd and ORAmean values shown are bootstrap estimates (with SEs in brackets).

†For each type of total corneal astigmatism measure, the measure with the lowest ORAsd is shown in bold.

SE, standard error.

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