Analysis of biometry and prevalence data for corneal astigmatism in 23 239 eyes

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PURPOSE: To present and analyze biometry data sets and prevalence data for corneal astigmatism in a large population.

SETTING: High-volume eye surgery center, Castrop-Rauxel, Germany.

METHODS: Axial length (AL), corneal radii, anterior chamber depth (ACD), and horizontal corneal diameter (white-to-white [WTW] distance) were optically measured by partial coherence interferometry (IOLMaster). Patient data sets acquired between 2000 and 2006 were reviewed and analyzed.

RESULTS: The study evaluated 23 239 data sets of 15 448 patients with a median age of 74 years. The mean values were as follows: AL, 23.43 mm ± 1.51 (SD); corneal radius, 7.69 ± 0.28 mm; WTW distance, 11.82 ± 0.40 mm; and ACD, 3.11 ± 0.43 mm. The ACD and axis of astigmatism were correlated with age. The AL, corneal radius, ACD, and WTW were correlated with one other. Eight percent of eyes had corneal astigmatism greater than 2.00 diopters (D), and 2.6% had more than 3.00 D. Astigmatism was with the rule (WTW) in 46.8% of eyes, against the rule in 34.4%, and oblique in 18.9%. High astigmatism was predominantly WTW.

CONCLUSIONS: The results in this analysis might provide normative data for cataract patients and a useful reference for multiple purposes. The correlation of AL with corneal radius, ACD, and corneal diameter in normal eyes was not present in eyes with extreme myopia or hyperopia.

Financial Disclosure: Neither author has a financial or proprietary interest in any material or method mentioned.

J Cataract Refract Surg 2010; 36:1479–1485 © 2010 ASCRS and ESCRS

The largest retrospective evaluation study of biometry data (7500 eyes) was published in 1980 by Hoffer.[1] Hoffer used immersion ultrasound A-scan, the most precise method available at the time. Since 1999, partial coherence interferometry (PCI) has become the standard for biometry measurements of the eye. The IOLMaster PCI platform (Carl Zeiss Meditec) measures axial length (AL), corneal radii, anterior chamber depth (ACD), and corneal diameter (white-to-white [WTW] distance) and is used routinely by most cataract surgeons in Germany. Surgeons can compare their results with data from other users to improve refractive results.[A] To our knowledge, there are no large series of biometry measurements with the PCI device in the literature. The goal of our study was to provide a new reference based on a large number group of patients.

Submitted: October 1, 2009.
Final revision submitted: February 27, 2010.
Accepted: March 18, 2010.

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PATIENTS AND METHODS

In this study, patient data sets acquired between 2000 and 2006 were reviewed and analyzed. Axial length (AL), corneal radii, anterior chamber depth (ACD), and horizontal corneal diameter (white-to-white [WTW] distance) were optically measured using an IOLMaster PCI biometer (software version 3.0). The measurements were routinely performed by technical staff.

Statistical data were analyzed using SimStat (version 2.5.5, Provalis Research) and Excel 2007 (Microsoft Corp.) software. The SRK/T formula[2] was used for statistical analysis of the theoretical IOL powers required to achieve emmetropia. The SRK/T formula was chosen because the

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doi:10.1016/j.jcrs.2010.02.025

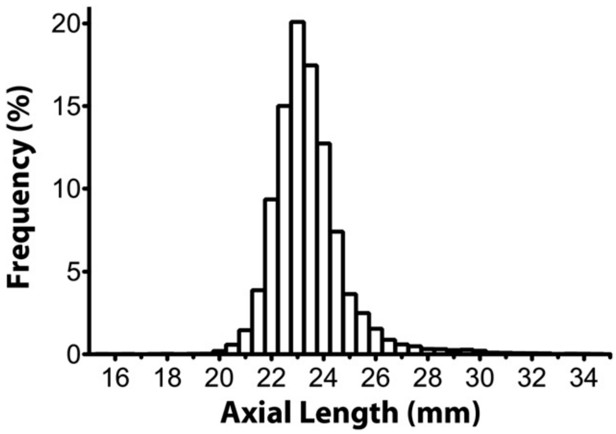

Figure 1. Frequency distribution of optically measured AL.

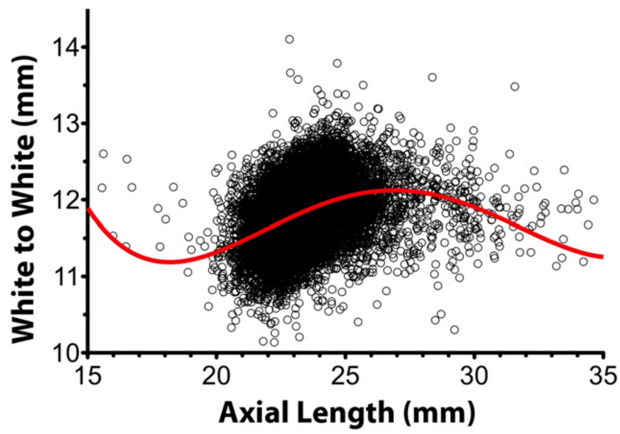

Figure 2. Horizontal corneal diameter (WTW) over AL (n =15 812 eyes). The red line is a fourth-order polynomial regression.

A-constant (119.2) is one of the most popular parameters used to describe IOLs with thin-lens formulas. The common range for widely used commercially available IOLs is +10.00 to +30.00 diopters (D).

RESULTS

This study evaluated 23 239 data sets of 15 448 patients with a median age of 74 years.

Biometry Measurements

The mean AL was 23.43 mm ± 1.51 (SD) (median 23.23 mm) (Figure 1) and the mean horizontal (WTW) corneal diameter, 11.82 ± 0.40 mm (Figure 2). The mean corneal radius was 7.69 ± 0.28 mm and the mean corneal power (refractive index 1.3375), 43.32 ± 1.50 D (Figure 3). There was a highly statistically significant negative correlation between corneal radius and patient age ($r = -0.104$, $P<.001$). The mean ACD (corneal epithelium to anterior lens capsule) was 3.11 ± 0.43 mm (Figure 4).

All 5 parameters were sex dependent. The mean values in male eye were somewhat larger than in female eyes in all dimensions. The male eyes were longer (23.77 mm versus 23.23 mm), had flatter corneal radii (7.77 mm versus 7.65 mm), had a deeper anterior chamber (3.12 mm versus mm 3.02), and had a larger corneal diameter (11.92 versus 11.77) (Table 1). All differences between the 2 sexes were highly statistically significant ($P<.001$, Kolmogorov-Smirnov 2-sample test).

The mean theoretical intraocular lens (IOL) power required to achieve emmetropia was 21.3 ± 4.4 D (median 21.8 D) (Figure 5). Of the theoretical IOL powers, 22 472 (96.7%) were within the common range of +10.00 to +30.00 D, 209 (0.9%) were above 30.00 D, and 558 (2.4%) were below 10.00 D.

Table 2 shows the frequency distribution of corneal astigmatism. The mean corneal astigmatism was 0.98

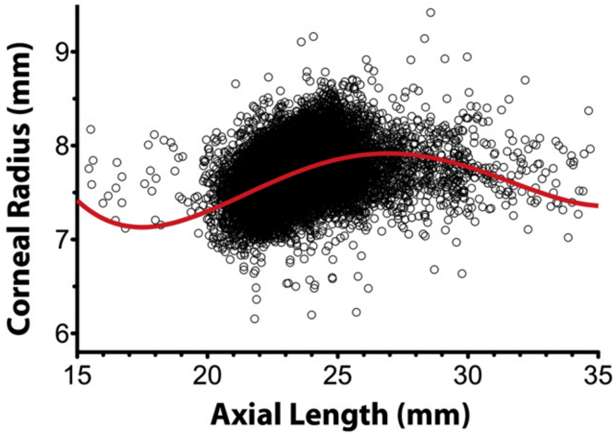

Figure 3. Scatterplot of corneal power over AL (N = 23 239 eyes). The red line is a fourth-order polynomial regression.

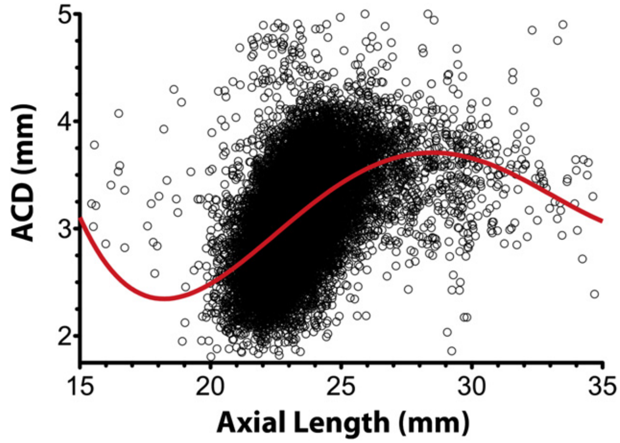

Figure 4. Scatterplot of preoperative ACD (corneal epithelium to anterior lens capsule) (N = 23 239 eyes). The red line is a fourth-order polynomial regression (ACD = anterior chamber depth).

Table 1. Biometric data broken down by sex (10 646 patients).

	Mean (mm) ± SD				
				Corneal Radius	
Group	AL	ACD	WTW	1	2
Right eyes					
Male	23.78 ± 1.44	3.12 ± 0.50	11.92 ± 0.40	7.84 ± 0.46	7.68 ± 0.44
Female	23.27 ± 1.51	3.01 ± 0.44	11.76 ± 0.38	7.73 ± 0.38	7.56 ± 0.37
Left eyes					
Male	23.75 ± 1.39	3.13 ± 0.61	11.92 ± 0.40	7.85 ± 0.39	7.68 ± 0.38
Female	23.20 ± 1.41	3.03 ± 0.54	11.76 ± 0.38	7.73 ± 0.31	7.56 ± 0.31

ACD = anterior chamber depth; AL = axial length; WTW = white-to-white diameter

± 0.78 D with a slight, but highly significant difference between right eyes (0.97 D) and left eyes (0.99 D) ($P < .01$). Approximately two thirds of all eyes had corneal astigmatism less than 1.00 D. Corneal astigmatism was 2.00 D or higher in 1860 of all eyes (8.0%), in 1789 right eyes (7.7%), and in 1952 left eyes (8.4%); the difference between right eyes and left eyes was statistically significant ($P < .001$).

Regarding distribution of the astigmatism axis, 10876 eyes (46.8%) had with-the-rule (WTR) astigmatism (axis of correcting minus cylinder 180 ± 30 degrees), 7971 eyes (34.3%) had against-the-rule (ATR) astigmatism (correcting minus cylinder 90 ± 30 degrees), and 4392 eyes (18.9%) had oblique astigmatism. The distribution was different when only cylinder values of 2.00 D or higher were examined, in which case 1217 eyes (64.7%) had WTR astigmatism, 460 eyes (24.5%) had ATR astigmatism, and 203 eyes (10.8%) had oblique astigmatism.

Figures 6 and 7 show the amount and frequency of astigmatism for each meridian (rounded to 5 degrees) in right eyes and left eyes separately. Figures 8 and 9 show the cumulative astigmatism per meridian as a double-angle plot; as can be seen, the higher astigmatism was predominantly WTR. The distribution was not mirror-inverted between right eyes and left eyes. Figure 10 shows the cumulative frequency of magnitude for corneal astigmatism.

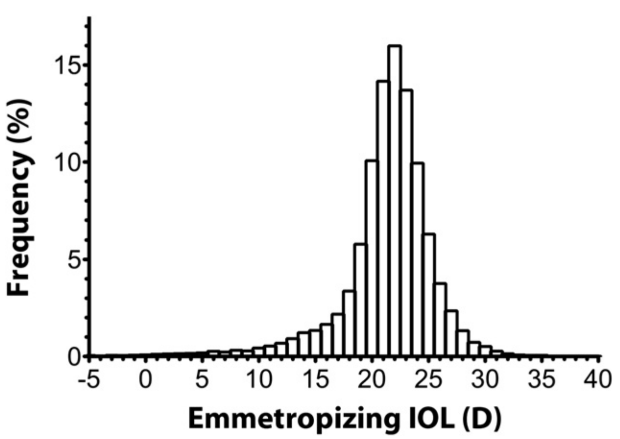

Figure 5. Theoretical IOL power to achieve emmetropia calculated by the SRK/T formula (A = 119.2) (IOL = intraocular lens).

Correlations

Axial length, corneal power, ACD, and corneal diameter were all correlated with one another; the correlations were highly statistically significant ($P < .001$). Anterior chamber depth was negatively correlated with age ($r = -0.283$). Table 3 shows the complete correlation matrix. The ACD generally increased and the corneal diameter generally decreased with AL. This was not the case in very short eyes and very long eyes, however. In normal eyes, there was no correlation or the positive correlations turned negative or vice versa. Table 4 shows the correlation matrix by AL. In eyes with a normal AL, the correlations were stronger. The amount of astigmatism did not appear to be age dependent, although its axis had a very strong correlation with age. The frequency of ATW astigmatism increased with age ($P < .001$, t test). The amount of astigmatism was positively correlated with corneal power in long eyes but negatively correlated with corneal power in short eyes.

Table 2 also compares the keratometric data in this study with refractive data from multifocal spectacle prescriptions (n = 78 205) based on the fact that corneal astigmatism is the main component of total astigmatism in higher refractive astigmatism.

DISCUSSION

Partial coherence interferometry[3] has become the new standard for measuring the AL in the human eye. Axial length measurements by PCI are better than those by applanation A-scan and at least equal to those by

Table 2. Corneal astigmatism and total refractive astigmatism in a presbyopic population in Germany (N = 23 239). Data derived from multifocal spectacle prescriptions (N = 78 205).

	Astigmatism Amount (D)						
Astigmatism Type	<1.0	≥1.0–<2.0	≥2.0–<3.0	≥3.0–<4.0	≥4.0–<5.0	≥5.0–<6.0	≥6.0
Corneal, n (%)	14 864 (63.96)	6495 (27.95)	1264 (5.44)	386 (1.66)	130 (0.56)	58 (0.25)	42 (0.18)
Refractive, n (%)	15 796 (67.97)	5240 (22.55)	1415 (6.09)	507 (2.18)	186 (0.80)	65 (0.28)	30 (0.13)

high-precision immersion A-scan, and they are highly operator independent.[4–7]

We collected all data measured with the IOLMaster PCI device since 2000. To our knowledge, results from this amount of biometry data have never been published. In 1980, Hoffer[1] reported results in a large data set in which immersion ultrasound was used for biometry. Although that was the technique of choice at that time, we decided to create a new reference using more modern equipment. We used PCI for AL measurement and the built-in automated keratometry and slitlamp for corneal radii, ACD, and corneal diameter measurements. Unfortunately, the PCI device we used cannot measure lens thickness.

The mean and median ALs in the eyes in our series were shorter than those in the Hoffer cohort using immersion A-scan (mean AL 23.65 mm)[1] and those reported by Haigis and Lege[8] and Olsen and Thorwest[9] using PCI. However, our values are almost identical to those in other studies in Europe and the United States.[10–14]

The AL actually measured (optical path length) was not identical to the output of the PCI device because the optical path length was calibrated against the Grieshaber Biometric System as a reference[6,8] and transformed internally to match that system's immersion A-scan output. A modified transformation might improve IOL calculation accuracy.[15,16] Partial coherence interferometry data can be compared with immersion A-scan data but not with contact A-scan data because of systematic and other errors.[17,18]

Differences between our data and those in other PCI studies may be the result of regional differences in populations because calibration between single IOLMaster devices seems to be good.[15] Although the literature describes an age dependence for AL,[1,14] this was not shown in our results. According to the literature, female eyes tend to be shorter than male eyes,[14,19] a finding our data uphold. Furthermore, we found that female eyes tend to have significantly steeper corneas,[20] shallower anterior chambers, and smaller WTW diameters.

Although our corneal radii data are almost identical to results in other studies,[1,8–10,12–14] the ACD values in our patients tended to be lower than immersion ultrasound measurements[1,10,12,14] and in the IOLMaster pilot study[8]; however, our ACD values were similar to those in the large group Olsen and Thorwest[9] evaluated using PCI. Corneal diameter was approximately 0.15 mm larger in all subgroups than in a group of eyes measured with scanning-slit topography (Orbscan, Bausch & Lomb)[21]; this may be due to different calibration of the devices. The positive correlation of AL with higher WTR astigmatism and the correlation of AL with

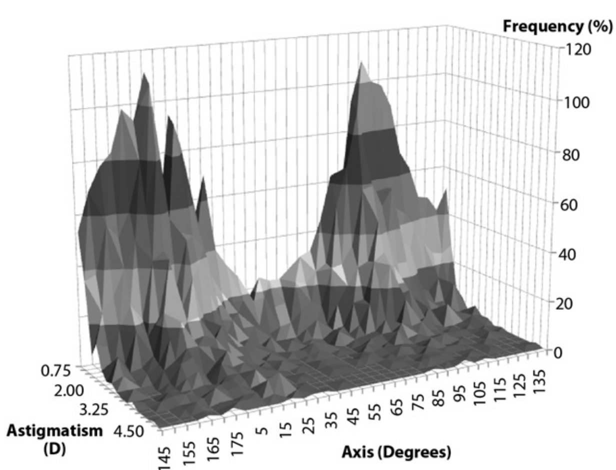

Figure 6. Frequency of corneal astigmatism of 0.75 D or higher in right eyes (n = 6927).

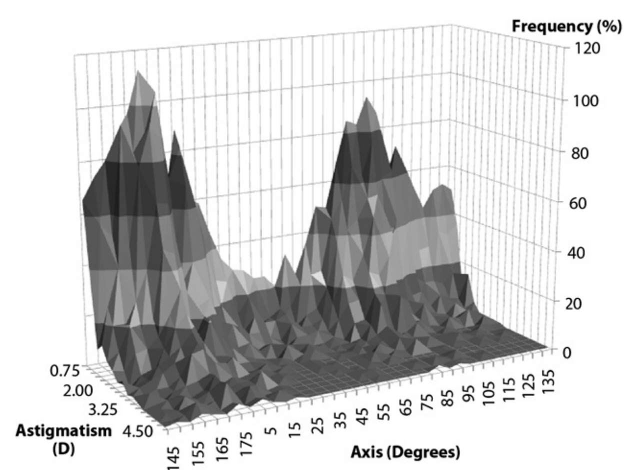

Figure 7. Frequency of corneal astigmatism of 0.75 D or higher in left eyes (n = 7352).

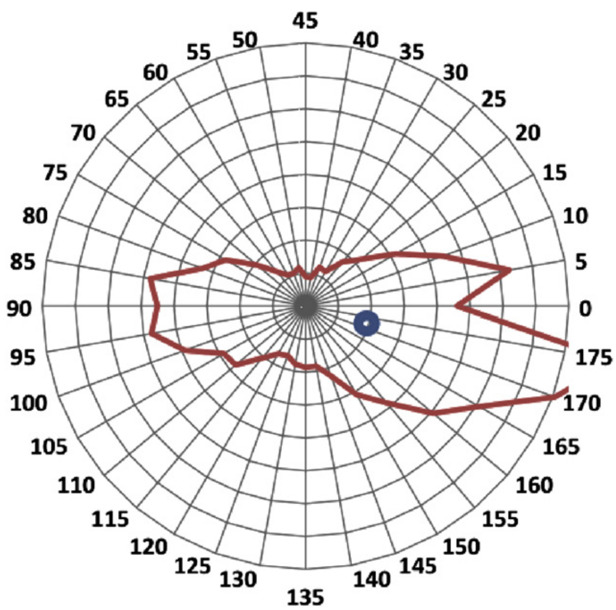

Figure 8. Double-angle plot of cumulative astigmatism per meridian (rounded to 5 degrees) in all right eyes (n = 10 963). The small blue circle marks the centroid.

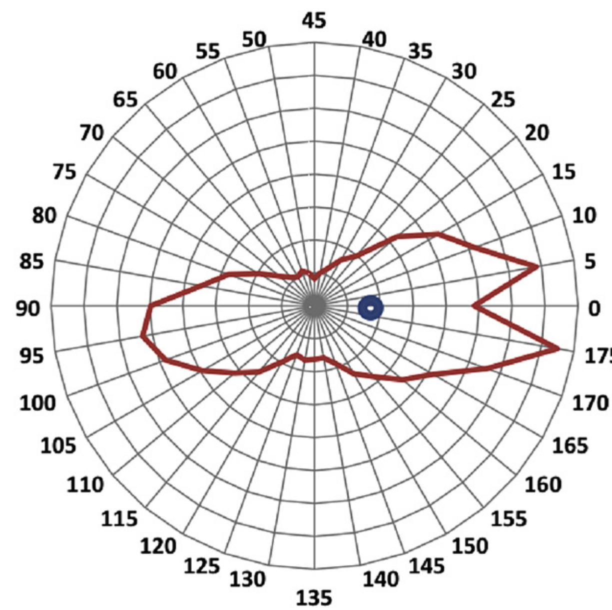

Figure 9. Double-angle plot of cumulative astigmatism per meridian (rounded to 5 degrees) in all left eyes (n = 11 294). The small blue circle marks the centroid.

corneal curvature were also described by Ninn-Pedersen.[19]

The strong statistical correlations between the AL, mean corneal radius, ACD, and WTW diameter in normal eyes were not present in eyes with an extremely long or short AL. This finding has been described in cases of high ametropia[21] and may be of importance in IOL calculation because parameters such as the mean corneal radius and ACD are used to predictor postoperative axial IOL position.[2,22–25,B] Regression models of normal eyes are not necessarily valid for very short or very long eyes. The anatomy of the anterior segment may be independent of the total length of the eye.

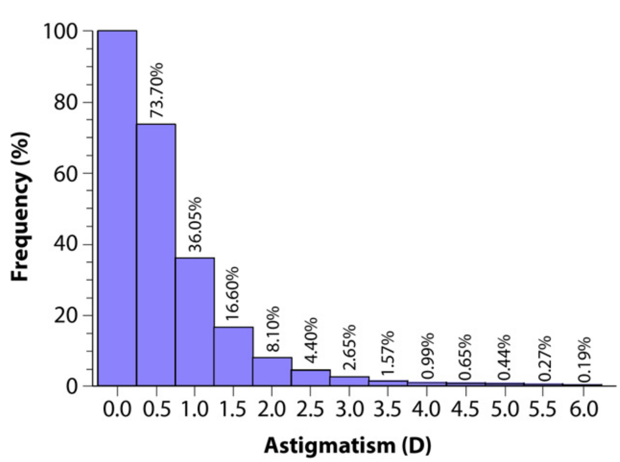

Figure 10. Cumulative frequency distribution of corneal astigmatism measured PCI (n = 23 239).

There are few reports in the literature of the epidemiology of corneal astigmatism; most studies evaluated refraction data. Prevalence data for corneal astigmatism is of interest to the cataract surgeon. If corneal astigmatism of 1.50 D or more is seen as an indication for a toric IOL, 16% of all eyes are potential candidates. If the line is drawn at 2.00 D, 8% of all eyes should have a toric IOL. Our mean astigmatism value of 0.98 D compares favorably with Hoffer's value of 1.00 D.[1] Two more recent studies[13,26] report a slightly higher percentage (22%) of eyes with astigmatism of 1.50 D or greater, although the means were identical to those in our study. Using temporal clear corneal incisions will reduce preexisting

Table 3. Pearson correlation matrix of all parameters measured by PCI (n = 15 812).

	Parameter				
Parameter	AL	ACD	WTW	K	ΔK
AL	—	0.324*	0.294*	−0.325*	0.024*
ACD	0.324*	—	0.292*	−0.035*	−0.034*
WTW	0.294*	0.292*	—	−0.471*	−0.050*
K	−0.325*	−0.035*	−0.471*	—	0.083*
ΔK	0.024*	−0.034*	−0.050*	0.083*	—

Δ = change; ACD = anterior chamber depth; AL = axial length; K = corneal power; WTW = white-to-white diameter
*$P < .001$

Table 4. Pearson correlation matrix of short eyes (below 5th percentile), long eyes (above 95th percentile), and normal eyes (5th to 95th percentile).

	Parameter				
Parameter	AL	ACD	WTW	K	Δ−K
AL ≤21.63 mm (n = 1107)					
AL	—	−0.038	0.000	0.037	−0.034
ACD	−0.038	—	0.201‡	−0.231	0.025
WTW	0.000	0.201‡		−0.439‡	0.041
K	0.037	−0.023	−0.439‡	—	−0.160‡
ΔK	−0.034	0.025	0.041	−0.160‡	—
AL ≥25.84 mm (n = 1152)					
AL	—	−0.093†	−0.145‡	0.072*	0.023
ACD	−0.093†	—	0.226‡	0.003	−0.021
WTW	−0.145‡	0.226‡	—	−0.483‡	−0.056
K	0.072*	0.003	−0.482‡	—	0.185‡
ΔK	0.023	−0.021	−0.056	0.185‡	—
AL 21.63–25.84 mm (n = 20 980)					
AL	—	0.345‡	0.355‡	−0.429‡	0.005
ACD	0.345‡	—	0.262‡	0.012	−0.036‡
WTW	0.355‡	0.262‡	—	−0.447‡	−0.054‡
K	−0.429‡	0.012	−0.447‡	—	0.083‡
ΔK	0.005	−0.036‡	−0.054‡	0.083‡	—

Δ = change; ACD = anterior chamber depth; AL = axial length; K = corneal power (calculated from corneal radii; refractive index 1.332); WTW = white-to-white diameter

*$P<.05$

†$P<.01$

‡$P<.001$

astigmatism in 34% of cases but will worsen it in 47% because the incision will be near the flattest meridian of the cornea.

In our analysis of multifocal spectacle prescription data, 9.5% of eyes had astigmatism of 2.00 D or higher. High astigmatism is relatively rare in the German population. In the same analysis, WTR astigmatism was less frequent than ATR astigmatism (40.6% versus 44.9%) in the presbyopic German population. This has been reported by other authors.[27] When the Javal rule (spectacle astigmatism = 1.25 × [corneal cylinder] + [−0.50 D × 90]) is considered and we assume ATR astigmatism of 0.50 to 0.60 D, the refractive data closely match our keratometric data.

The crystalline lens with slight ATR astigmatism (mean 0.60 D) may have an increase in astigmatism with aging, and the frequency of ATR astigmatism continually increases with age.[28–31] In addition, the cornea might change its flattest meridian toward the 90-degree axis with age.[31] A large study[20] found a significant increase in refractive and corneal ATR astigmatism. Similarly, the prevalence of ATR corneal astigmatism was associated with age in our study. The magnitude of corneal astigmatism had little dependency on age ($r = 0.03$ $P<.001$), in contrast to the refractive astigmatism in the entire population of our clinic (N = 82 540; unpublished data). In the latter cohort, the magnitude of corneal astigmatism was strongly correlated with age ($r = 0.22$, $P<.001$). This is mainly the result of ATR astigmatism within the crystalline lens, which tends to increase with age.

In long eyes in our study, high astigmatism was associated with steep corneas whereas in short eyes, high astigmatism was associated with flat corneas. To our knowledge, this relationship has not been described in the literature.

When the crystalline lens is removed, total astigmatism is exclusively determined by the cornea; the same is true for very high astigmatism (≥ 3.0 D) in phakic eyes. In pseudophakic eyes, small amounts of refractive cylinder can occur because IOL decentration and tilt can induce coma and other higher-order aberrations. In our study, high natural astigmatism was predominantly WTW; the astigmatism was WTW in 61.9% of all eyes and ATR in 28.8%, which is congruent with the PCI data.

In conclusion, we report biometry and astigmatism data in a large cohort. Our findings can serve as an important normative reference for ophthalmologists and may help the industry tailor toric IOLs to the needs of the market.

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