# 60 Astigmatism of the Cornea

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Accurate measurement of total corneal astigmatism is a critical element in correcting astigmatism during cataract surgery. The prevalence of anterior corneal astigmatism ≥1.0 D has been reported to range from 32 to 41% [1–4]. Using partial coherence interferometry (IOLMaster), in 23,239 eyes, Hoffmann and Hütz [5] reported that 73.7% of eyes had anterior corneal astigmatism ≥0.5 D, and 36.1% had anterior corneal astigmatism ≥1.0 D.

Traditionally, corneal astigmatism has been calculated based on anterior corneal measurements only. The magnitude of posterior corneal astigmatism was thought to be clinically negligible because of the small difference in refractive indices between the cornea and aqueous. This chapter will discuss corneal astigmatism calculated based on anterior corneal measurement, the contribution of posterior corneal astigmatism to total corneal astigmatism, corneal astigmatism changes with aging, and higher-order aberrations of the cornea.

## Corneal Astigmatism Based on Anterior Corneal Measurement

Until recently, we could only measure the anterior corneal surface. Technologies used to measure the anterior corneal surface include manual and automated keratometers, Placido disk corneal topographers, and reflection-based topographers or biometers.

To compensate for the negative power of the posterior surface, a corneal index of refraction (1.3375) is typically used to estimate the refractive power of the entire cornea. The origin of 1.3375 as the keratometric index of refraction is Gullstrand's corneal model with anterior and posterior radii of curvature of 7.7 mm and 6.8 mm, respectively [6, 7]. The ratio of posterior-to-anterior radii of curvature is 6.8/7.7 = 0.883, which is higher than those reported recently using the Scheimpflug devices. Using the Pentacam, Dubbelman et al. [8] reported the posterior/anterior ratio to be on average 0.813. Using the Galilei Dual Scheimpflug Analyzer (Ziemer Ophthalmic System AG, Port, Switzerland) [ 9], we found that the average ratio of posterior/anterior radii of curvature (P/A ratio) was 0.82 in normal eyes, ranging from 0.73 to 0.87. We have found a mean P/A ratio of 0.76 (range 0.69–0.83) in myopic-LASIK/PRK eyes, 0.86 (range 0.82–0.91) in hyperopic-LASIK/PRK eyes [9], and 0.93 (but with a huge range of 0.67–1.25) in post-radial keratotomy eyes (unpublished data). In addition, various types of keratoplasty can alter the P/A ratio, as can corneal scarring or any other process that alters only anterior corneal curvature. This indicates that the estimation of total corneal power using anterior corneal curvature measurements and the standard refractive index of 1.3375 is often inaccurate, par-

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ticularly in nonvirgin corneas. As we discuss below, this also has important implications for estimating the contribution of the posterior cornea to total corneal astigmatism.

## Contribution of Posterior Corneal Astigmatism to Total Corneal Astigmatism

The disparity between refractive and anterior corneal astigmatism was first noted by Javal [10]. The potential cause was felt by many to be lenticular astigmatism, but Tscherning surmised that it could be due to posterior corneal astigmatism [11]. However, only recently have clinical devices capable of measuring posterior corneal astigmatism become available. The measurement modalities include slit-scanning imaging, Scheimpflug imaging, optical coherence tomography (OCT), and detection of the second Purkinje images.

Several studies have evaluated posterior corneal astigmatism using different methodologies. The main findings of posterior corneal astigmatism and its contribution to the total corneal astigmatism are summarized as follows [12–15]:

- The mean magnitude of posterior corneal astigmatism is around −0.20 to −0.30 D, but there is wide variability.
- In the majority of corneas, the steepest meridian of the posterior corneal surface is aligned vertically (Fig. 60.1). Since the posterior corneal surface has negative power, a steeper curvature at the 90° meridian creates net refractive power horizontally. This results in most corneas having more net against-the-rule (ATR) astigmatic refractive power than is measured from the anterior corneal surface. Thus, posterior corneal astigmatism partially compensates for anterior corneal astigmatism in corneas that have with-the-rule (WTR) astigmatism on the anterior corneal surface, but it increases total corneal astigmatism in corneas that have ATR anterior astigmatism.
- In corneas with WTR astigmatism on the anterior corneal surfaces, the magnitude of posterior corneal astigmatism increases with increasing amount of anterior corneal astigmatism, ranging up to over 1 D in eyes with anterior WTR of 4 D or more (Fig. 60.2 top). This indicates that compared to the total corneal astigmatism calculated using a fixed corneal refractive index based on the ante-

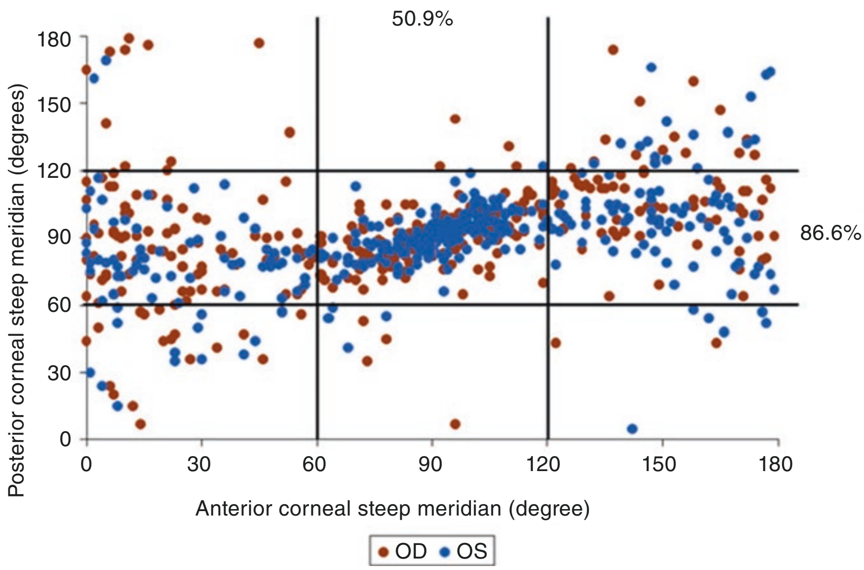


**Fig. 60.1** Location of the steep meridian on anterior and posterior corneal surfaces. (Adopted from [12])

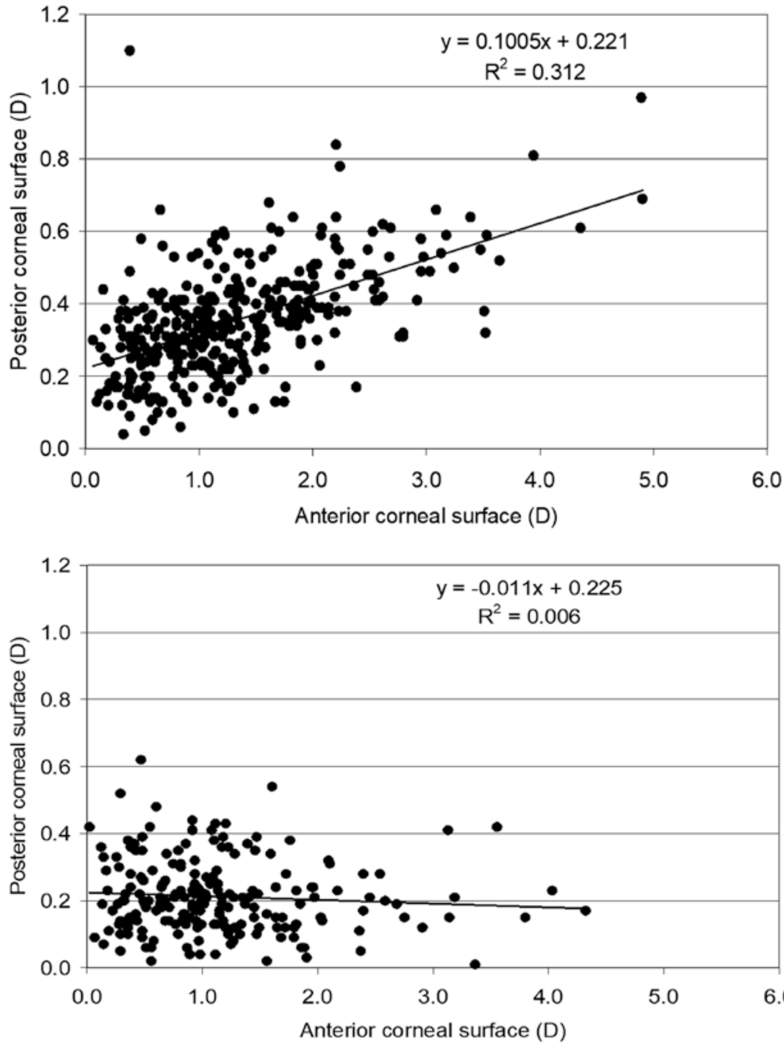


**Fig. 60.2** Magnitude of astigmatism on the anterior corneal surface and posterior corneal surface in eyes with with-the-rule (top) and against-the-rule (bottom) astigmatism on the anterior cornea. (Adopted from [12])

rior corneal surface only, the total corneal astigmatism magnitude is smaller, and more so in eyes with large amounts of anterior corneal astigmatism. If the posterior corneal astigmatism is ignored, overcorrection can occur when correcting astigmatism with toric IOLs.

- In corneas with ATR astigmatism on the anterior corneal surfaces, posterior corneal astigmatism is relatively constant around 0.3 D and does not increase with increasing amount of anterior corneal astigmatism (Fig. 60.2 bottom). If the posterior corneal astigmatism is ignored, undercorrection can occur.
- However, the location of the steep meridian of the posterior corneal surface is more variable in eyes that have oblique and ATR astigmatism, as can be seen in Fig. 60.1. In addition, in a study of 3818 corneas measured with the Pentacam, Tonn et al. [14] reported the variability of the location of the steep posterior corneal meridian as a function of the steep anterior corneal meridian.
  - As Fig. 60.3 shows, the percentage of corneas with the posterior surface steepest vertically decreases as a function of the change in anterior corneal astigmatism from WTR to oblique to ATR.

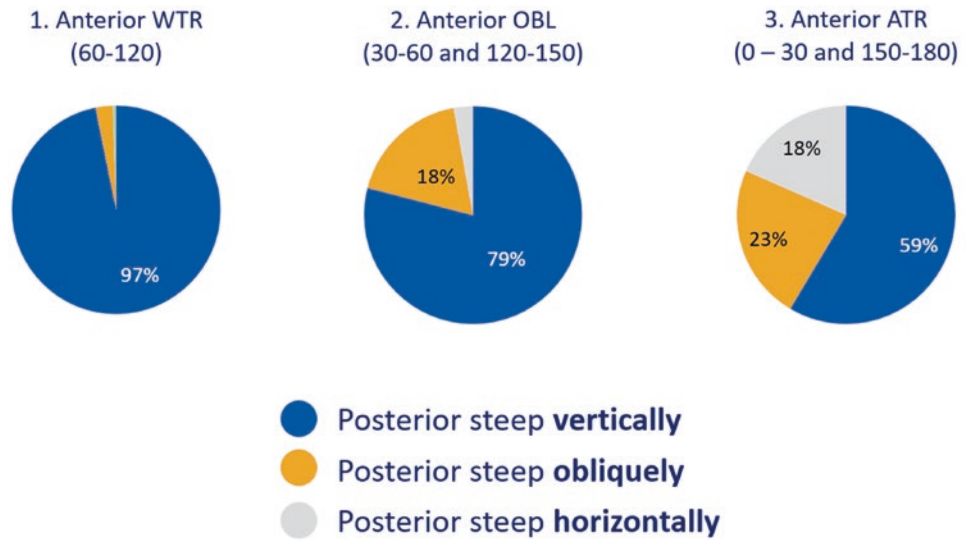


**Fig. 60.3** Percentage of eyes with vertical, oblique, and horizontal steep meridian on the posterior corneal surface in eyes with anterior with-the-rule (WTR), oblique (OBL), and against-the-rule (ATR) astigmatism. (Adopted from [14])

- These studies highlight the impact and variability of posterior corneal astigmatism and the need to get reliable measurements in patients undergoing cataract surgery.
- There are two ways to factor posterior corneal astigmatism into toric IOL calculations: (1) mathematical models based on prior toric IOL outcomes and (2) direct measurement of posterior corneal curvature.
  - Studies to date largely suggest that the former are more accurate for determining IOL toricity [16], perhaps due to the inaccuracy of our devices and/or the fact that other factors such as IOL tilt contribute to refractive astigmatism.

In summary, ignoring posterior corneal astigmatism may yield an incorrect estimation of total corneal astigmatism. In general, selecting toric intraocular lenses based on anterior corneal measurements could lead to overcorrection in eyes that have WTR astigmatism and undercorrection in eyes that have ATR astigmatism. More accurate methods of measuring posterior corneal astigmatism may be needed, and optimal toric IOL formulas will incorporate this as one of several elements in postoperative refractive astigmatism.

## Corneal Astigmatism Changes with Aging

In case series studies using Scheimpflug technology, studies reported that, with increasing age, the steep anterior corneal meridian tends to change from vertical to horizontal, while there is minimal change in the steep posterior corneal meridian [12, 14].

Hayashi and colleagues [17] investigated long-term changes in anterior corneal astigmatism with aging, comparing eyes that underwent sutureless cataract surgery and those that did not undergo surgery. They evaluated the keratometric cylinder between baseline and 5 years after baseline and between 5 and 10 years. Corneal astigmatism after cataract surgery showed a long-term ATR change with aging, and this change was similar to that of normal cornea without surgery. In another study, Hayashi et al. [18] examined how corneal astigmatism changes with age over 20 years after cataract surgery and again assessed whether the changes differ from those in eyes that did not have surgery. They found that the corneal astigmatism continued to change toward ATR astigmatism over 20 years after cataract surgery, and this change was similar in eyes that did not have surgery. The mean ATR change over

20 years is approximately 0.65 D, with a 0.30–0.35 D of change over each 10-year period.

These findings suggest that the against-the-rule change that occurs with aging should be taken into consideration at the time of cataract surgery and that a reasonable astigmatic target is a small amount of WTR astigmatism [13].

## Higher-Order Aberrations of the Cornea

In addition to astigmatism, the cornea also has higher-order aberrations and irregular astigmatism. In a previous study [19], we found that the anterior corneal wavefront aberrations varied greatly among subjects, with higher-order Zernike coefficient values ranging from −0.579 to +0.572 μm. Higher-order aberration root-mean-square and coma root-mean-square values increased with aging (Fig. 60.4). Nearly all virgin corneas had positive fourth-order spherical aberration, but these values did not change with aging. Similarly, Oshika et al. [20] reported that spherical-like aberrations did not vary significantly with aging, whereas comalike aberrations of the cornea correlated with age, implying that the corneas become less symmetrical along with aging.

Of relevance to astigmatism correction, corneal higher-order aberrations, particularly coma, can impact the patient's perception of astigmatism during refraction and thereby contribute to refractive astigmatism [21]. How this affects toric IOL outcomes remains to be elucidated.

## Future Directions/Needs

We often encounter clinically significant differences in corneal astigmatism values obtained from different devices. Although this may be caused by different areas of the astigmatic cornea measured and different algorithms employed by different devices, accuracy, repeatability, and reproducibility of corneal astigmatism measurements by these devices may also need improvements.

In a recent study [15], we compared corneal astigmatism obtained from an OCT-based biometer and a Dual Scheimpflug Analyzer (Galilei, DSA). Comparing the total corneal astigmatism values from these two devices, 84.3 and 98.9% of eyes had differences in magnitude of ≤0.50 and ≤1.0 D, and in eyes with OCT total keratometry astigmatism of ≥0.5 D, 34.5% and 60.1% of eyes had differences in the steep meridian of ≤5 and ≤10°, respectively; 52.8–63.5% of eyes had vec-

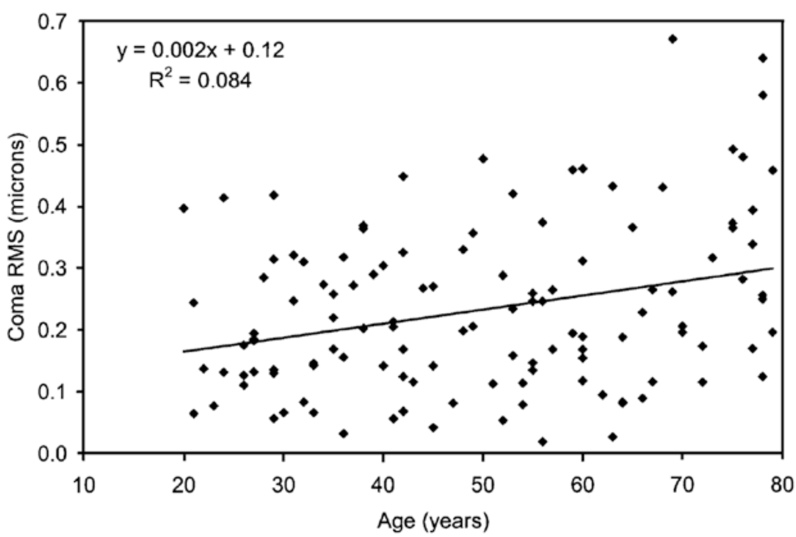


**Fig. 60.4** Scattergram of corneal coma root-mean-square values as a function of age (Pearson's correlation coefficient $r = 0.290$, $P < 0.001$). (Adopted from [19])

tor differences of ≤0.50 D. These results indicate that there were clinically significant differences in total corneal astigmatism obtained from OCT and DSA devices.

The future direction is the evolution of current devices and possibly the development of new ones that will enable us to more accurately measure total corneal astigmatism.

## Conclusion

Total corneal astigmatism is determined by both the anterior and posterior corneal surfaces. Ignoring posterior corneal astigmatism may yield an incorrect estimation of total corneal astigmatism. Correcting corneal astigmatism based on anterior corneal measurements only could lead to overcorrection in eyes that have WTR astigmatism and undercorrection in eyes that have ATR astigmatism. The ATR change that occurs with aging should be taken into consideration at the time of cataract surgery. Devices with more accurate and repeatable anterior and posterior corneal measurements are desirable.

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