ARTICLE

Standards for analyzing astigmatic outcomes: Part I: astigmatism basics

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Astigmatism is the difference between the orthogonal principal planes of minimal and maximal powers of a toric surface, lens, or refraction. Corneal astigmatism is a common condition, and studies indicate that over 60% of individuals have more than 0.50 diopters of astigmatism. Corneal astigmatism is measured in various ways, and measurements from different devices are usually not interchangeable because of variations in technology and the corneal regions that are imaged. The integrity of the ocular surface is critically important for accurately measuring corneal astigmatism. Optimizing the ocular surface before cataract surgery can significantly improve the accuracy of preoperative astigmatism measurements and refractive outcomes. It is advisable to obtain at least 2 or preferably 3 measurements when measuring corneal astigmatism. When a discrepancy in astigmatism meridian and magnitude occurs between the measurements, it is advisable to settle or at least minimize this discrepancy by repeating the measurements after optimizing the ocular surface. Posterior corneal astigmatism is an important component of total corneal astigmatism. Lens tilt can also induce visually significant refractive astigmatism and ideally should be accounted for in toric intraocular lens planning.

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Astigmatism analysis can be a complex, daunting, and sometimes contentious endeavor because of the complex nature of the topic, the variety of approaches available, and the shifting terminology. Over the past 3 decades, a variety of analytical methods have been proposed for predicting the residual refractive astigmatism after cataract and refractive surgery with the dual goals of guiding surgeons to provide optimal correction of astigmatism and enabling researchers to analyze and present outcomes of procedures that alter astigmatism. Although many of the new developments are helpful, the lack of general consensus on terminology and approach make it increasingly difficult to effectively compare and evaluate research in the area of astigmatism.

To bring clarity to the topic of astigmatism analysis for all current and future researchers, the *Journal of Cataract & Refractive Surgery* formed a working group to (1) establish astigmatic reporting guidelines based on sound optical principles and (2) provide new astigmatism calculation tools that simplify the process and allow researchers to reliably calculate accurate and reproducible results.

DEFINING ASTIGMATISM

In a *spherical* (*stigmatic* or *point-like*) optical system, a point in the object space is focused as a point image. An object located in the far point is focused on the retina. Objects from any other positions are defocused.[1]

In a *regular astigmatic* optical system, an object point is focused as 2 mutually perpendicular line segments delineating the Sturm interval.[1] Stated another way, astigmatism is the difference between the orthogonal principal planes of minimal and maximal powers of a toric surface, lens, or refraction. The curvature difference can be transformed to dioptric power using the radii of curvature and refractive indices of the refractive surface and surrounding media.[2] The optical effects of ocular astigmatism are blurring at all fixation distances because of a lack of point focus and, when corrected with cylindrical lenses, causes distortion in various meridians because of unequal

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magnification of the retinal image. Sphere and regular astigmatism are lower-order aberrations, correctable with spectacles or contact lenses. However, the optical quality of the human cornea is inferior to a diffraction-limited lens, with mean higher-order aberrations (also termed *irregular astigmatism*) above 0.4 μm.[2,3] Therefore, a significant amount of irregular astigmatism is present in the cornea of every human eye, but the amount of irregularity in most eyes is sufficiently small to allow corrected vision of 20/20 or better when the pupil size is between 2.5 mm and 4.5 mm.[4]

A vector is an entity that has both a magnitude and a direction. Geometrically, we can picture a vector as a directed line segment, whose length is the magnitude of the vector and with an arrow indicating the direction. On double-angle plots, the vector is shown as a point representing the tip of the arrow, and the tail at the origin and line segment have been omitted for simplicity.

Astigmatism is represented in a 2-dimensional space by 2 correlated values: magnitude and direction. The direction is actually bidirectional because the axes or meridians are made up of 2 semimeridians. For example, vertical astigmatism is composed of the 90-degree and 270-degree semimeridians, but we simply specify the smaller angle, since the larger angle is always 180 degrees away (Figure 1). This concept of astigmatism is confirmed in the practical situation of clinical refraction, where, for example, a corrective cylinder of given power may be placed in the trial frame or phoropter in an axis of 30 degrees or rotated 180 degrees to 210 degrees, providing the identical optical effect. Astigmatism in its traditional format is therefore not a vector, and calculations of means, spreads, prediction errors, etc. cannot be performed with our usual algebraic methods.[5] Stokes realized that, if the 2 angles were doubled, they would become the same and have only 1 direction (2 × 90 degrees = 180 degrees and 2 × 270 degrees = 540 degrees = 180 degrees). After the angle is doubled, it satisfies the definition of a Euclidean vector because there is only 1 direction. The proper term is double-angle astigmatism vector (Figure 1). All vector algebra and statistical analyses can then be performed, after which the double angle is then halved for the single-angle result. The double-angle astigmatism vector can be broken down into 2 component eigenvectors with cosine and sine functions as is described in Part II.

ASTIGMATISM: SOURCES AND MEASUREMENT

Refractive and Corneal Formats for Astigmatism

The direction of *corneal* astigmatism is usually given by the principal *meridian* of maximal power. The astigmatism M in diopters along the meridian Θ in degrees is symbolized as (M @ Θ). The direction of *refractive* astigmatism is provided by the *axis*, perpendicular to the plane of maximal power. The astigmatism M in the axis (Θ + 90) is symbolized as (M × [Θ + 90]).

Refractive astigmatism is provided by subjective refraction or autorefraction. Corneal measurements identify the radii of curvature and meridians along the 2 orthogonal principal meridians. The *curvature* C with units in diopters (D) is the reciprocal of the radius R of curvature with units in meter: C = 1/R.[1] The radii of curvature are converted to power K (D) with the paraxial formula: $K = (n_2 - n_1)/R$, where n_1 and n_2 are the refractive indices of the first and second media along the optical pathway. The refractive index (n_1) of air = 1.0 is used in assessment of anterior corneal surfaces.

Anterior corneal astigmatism is based on keratometry or corneal topography and uses the actual refractive index of corneal tissue n_2 of 1.376. *Keratometric astigmatism* also relies on measurement of the anterior surface only, but assumes a fixed correlation between anterior and posterior corneal curvatures. It uses an effective (or fictitious) refractive index n_2 of 1.3315 to 1.3375 to account for the mean negative posterior corneal power. *Posterior corneal astigmatism* uses the refractive indices of cornea (n_1 = 1.376) and aqueous (n_2 = 1.336). *Total corneal astigmatism* uses tomographic measurements of both surfaces and of corneal thickness to allow thick-lens optics or ray tracing. *Internal ocular astigmatism* is caused by the posterior corneal and lenticular toricities in association with decentration and tilt of these lenses. It is calculated as the vector difference between the refractive astigmatism (converted from the vertex to the anterior corneal plane) and anterior corneal astigmatism.

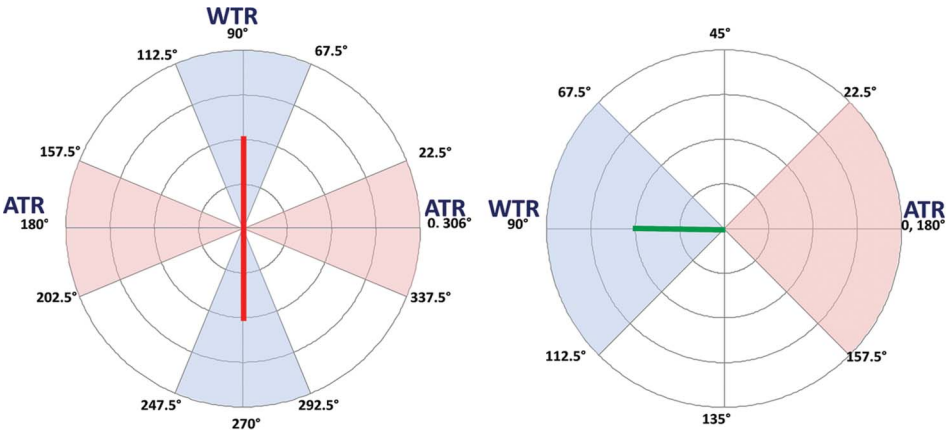

Figure 1. Astigmatism of 2 D @ 90 degrees plotted on a single-angle graph (*red line*, *left*) and double-angle graph (*green line*, *right*). Note that there are 2 semimeridians in the single-angle graph. Doubling the angle converts these into a vector that allows calculations of means, spreads, prediction errors, etc (each ring = 1 D).

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Corneal Astigmatism and Population Distribution

Corneal astigmatism is a common condition. In his classic study of anterior corneal keratometric astigmatism, Hoffer found that 69% of individuals had more than 0.50 D of astigmatism, 39% more than 1.0 D, and 22% more than 1.5 D.[6] In a large UK study of patients undergoing cataract surgery, 78% had more than 0.5 D of anterior corneal astigmatism, 40% had more than 1 D, and 21% had more than 1.5 D.[7] Similar distributions have been reported in studies from India, China, and Brazil.[8–10] A recent study of patients undergoing cataract surgery reported that total corneal astigmatism of ≥ 0.5 D was present in 77% of eyes, with 59.1% having ≥ 0.75 D.[11]

Studies of cataract surgery patients around the world have reported similar distributions in anterior corneal astigmatism orientation, with approximately 30% to 35% having with-the-rule (WTR) astigmatism, 40% to 45% having against-the-rule (ATR) astigmatism, and 17% to 20% having oblique astigmatism.[7,9] The similarity of these distribution patterns of corneal astigmatism magnitude and orientation suggest that guidelines for astigmatism correction are applicable worldwide.

The orientation of anterior corneal astigmatism varies as a function of its magnitude (Figure 2).[12] As the magnitude increases, the incidence of ATR astigmatism is nearly constant, varying from 26% to 31%. By contrast, the incidence of WTR astigmatism increases from 26% to 64%. This increase is attributable to the decreased incidence of higher levels of oblique astigmatism from approximately 20% to less than 5%.

Astigmatism in right and left eyes are usually mirror images of each other about the vertical axis. In the prevalence percentages in Figure 2, the left eyes have been mirrored so that temporal and nasal are the same for right and left eyes. The article by Holladay et al. shows that, when the back-calculated total SIA was determined from 20 surgeons who used temporal corneal incisions, the result in the left eye was the mirror of the right eye.[13] If the investigator shows that measurement results for left eyes are mirror images of the right, then it is appropriate to mirror left-eye images before analysis of astigmatism.

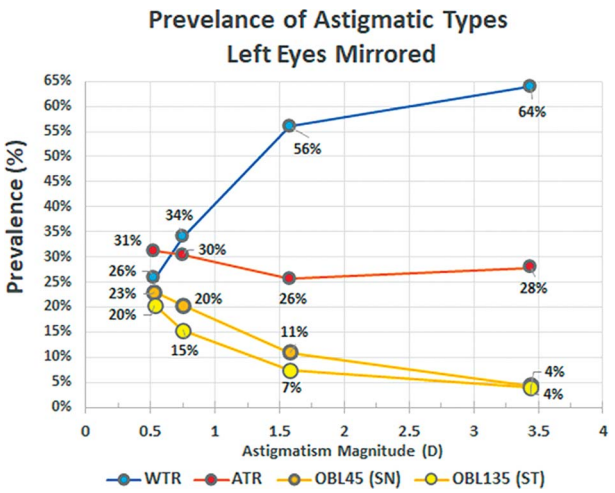

Figure 2. Prevalence of the orientation of the astigmatism as a function of the magnitude with left eyes mirrored.[11]

Corneal astigmatism changes with age. Most population studies show an age-related shift in anterior corneal astigmatism from being steeper vertically (WTR) to steeper horizontally (ATR), with 1 study reporting that astigmatism is fairly stable until age 50 years.[6,14–19] For patients older than 50 years, a mean ATR drift of 0.25 to 0.4 D per decade has been reported.[20] In contradistinction, studies have reported modest changes in posterior corneal astigmatism with aging, with over 90% of corneas steep vertically at ages 20 to 29 years, decreasing by approximately 10% by ages 70 to 79 years.[14,16,18,19]

Corneal Imaging Technologies and Influencing Factors

Because astigmatism is measured in various ways, some clarification of terminology is in order.[21] Keratometric astigmatism is anterior corneal astigmatism measured in a ring of the cornea, approximately 3 to 4 mm in diameter (nominally 3.2 mm for a 44 D cornea), as is done with the classic Bausch & Lomb keratometer. Corneal topographers and tomographers can measure astigmatism in annular zones and over zones of varying diameter. Total corneal astigmatism ideally is calculated by ray tracing using measurements of anterior and posterior curvature and corneal thickness. However, various imaging technologies and algorithms are used to calculate total cornea astigmatism, and there is no groundtruth for validation of the accuracy of these values.[22]

Differences Among Imaging Technologies

Corneal astigmatism measurements from different devices are in general not interchangeable.[17–19] There are several reasons for this:

1. A number of technologies are used to measure corneal astigmatism, including reflection (rings or single-point mires), Scheimpflug imaging, and optical coherence tomography.
2. The normal virgin cornea is aspheric and almost always steeper centrally (prolate), and corneal astigmatism differs from the central cornea to the midperiphery, especially in eyes with high, oblique, and against-the-rule astigmatism.[23] As a result, measurements at different distances from the center can lead to differences in both magnitude and axis. Commonly used optical biometers measure corneal astigmatism in zones that are 2 to 2.5 mm in diameter.[23,24]

Variability in measurements of corneal astigmatism using different technologies poses challenges in clinical decision making. Zonal keratometry (topography/tomography) over the patient's mesopic entrance pupil has the advantage of sampling a much larger region of the central cornea, and the zone size can be customized to the specific patient.

The Importance of Optimizing the Ocular Surface

The integrity of the ocular surface is critically important for accurately measuring corneal astigmatism.[25] A poor or

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unstable tear film that reduces the quality of corneal reflections can easily compromise the K readings.[2] Untreated tear deficiency before cataract surgery can lead to refractive surprises and dissatisfied patients.[9,25] In 1 study, ocular surface management in dry eye patients before cataract surgery with tear film stabilization was shown to modify the magnitude and meridian of astigmatism in 76% of eyes, ultimately affecting the astigmatism treatment modality in 68% of eyes, with changes in procedures (among toric intraocular lens [IOL], relaxing incisions, or no astigmatism correction) and in magnitude and/or alignment of toric IOLs or relaxing incisions.[26]

Caution is needed when using artificial tears before keratometry and biometry measurements.[27] Röggla et al. found that administration of artificial tears can highly affect K readings, especially in dry eye patients and when measurements are performed within 5 minutes of tear instillation.[28] Even in healthy patients, similar findings could be observed by Schug et al. when using the IOLMaster 700, the Pentacam AXL and the Galilei G6.[29] As reported by the ASCRS Corneal Clinical Committee, optimizing the ocular surface before cataract surgery can significantly improve the accuracy of preoperative astigmatism measurements and, therefore, refractive outcomes.[30]

Measurements in Irregular Corneas

As noted above, every cornea has some component of irregular astigmatism. Visually significant irregular corneal astigmatism is often challenging to treat because of the high variability of measurements. When a discrepancy in astigmatism meridian and magnitude occurs among measurements, it is first advisable to settle or at least minimize this discrepancy by repeating the measurements after optimizing the ocular surface. Zonal topography/tomography over the patient's mesopic entrance pupil has the advantage of determining the optical power of the corneal lenticule that provides the foveal image.

It is difficult to measure total corneal astigmatism in eyes that have undergone corneal refractive surgery because:

- There is increased irregular astigmatism in the anterior cornea.[31]
- If measuring only the anterior corneal curvature, it is more challenging to accurately estimate total corneal astigmatism, since the surgically altered anterior corneal astigmatism does not retain a normal mathematical relationship with posterior corneal astigmatism. Direct measurement of posterior corneal astigmatism may improve the accuracy of the estimation of total corneal astigmatism in these eyes.[32–34]

Even with these limitations, 1 study reported good results with toric IOLs implanted in post–laser in situ keratomileusis (LASIK) eyes.[35] In eyes that met 3 criteria—regular bowtie astigmatism within the central 4-mm zone and a difference in corneal astigmatism of less than 0.75 D and 15 degrees between 2 imaging devices—the percentage of eyes with postoperative refractive astigmatism of 0.5 D or less was 80% for eyes that had undergone myopic LASIK and 84% for eyes that had undergone hyperopic LASIK.

Keratoconus corneas present an even greater challenge because of the irregular astigmatism that leads to lower measurement repeatability.[36] Reproducibility is inversely related to the severity of keratoconus, and it is especially poor for eyes with K above 50 D.[37,38]

Number of Measurements to Obtain

Considering the above factors, it is advisable to obtain at least 2 or preferably 3 measurements when measuring corneal astigmatism. One measurement would be with the biometer LEDs for measuring anterior corneal power, which measure 6 to 32 points, and another might be with a topographer/tomographer, which measures over 10 000 points and can be used to provide data over central zones of varying diameter. The third measurement could be a repeated measurement with the same biometer at a different time or day or one obtained with a third device. Topography/tomography is strongly recommended as it is required to detect irregular astigmatism, corneal ectatic disease, and, with Placido imaging, subtle surface irregularities.

INTERNAL ASTIGMATISM

Posterior and Total Corneal Astigmatism

For over a century, it has been recognized that in human eyes, there is a difference between the refractive and anterior corneal astigmatism, with typically less WTR and more ATR astigmatism in the refraction than in the anterior cornea.[39] The crystalline lens and posterior cornea have both been implicated to explain this disparity. As it turns out, both are indeed involved. With the emergence of new imaging technologies, such as Scheimpflug imaging, optical coherence tomography, and light reflection analogous to keratometry, many studies have elucidated the significant contribution of posterior corneal astigmatism to total corneal astigmatism. It has been reported that, because of the influence of posterior corneal astigmatism, in nearly 30% of the eyes, the total corneal astigmatism differed from the anterior corneal astigmatism by more than 0.5 D and more than 10 degrees in meridian.[40] Using Scheimpflug imaging technology, it has been shown that mean posterior corneal astigmatism is approximately 0.5 D in corneas that have WTR anteriorly and 0.3 D in corneas that have ATR anteriorly.[19] In addition, a corresponding increase in posterior corneal astigmatism was found in eyes with increasing amounts of anterior WTR astigmatism, whereas in eyes with increasing amounts of ATR astigmatism, posterior corneal astigmatism remained relatively constant.[19] Recent progress in imaging technologies has enabled us to achieve excellent repeatability in the measurement of total corneal astigmatism in normal eyes, as reported with multiple devices; however, there remains some uncertainty about the accuracy of these measurements because of the inability to validate them.[41,42]

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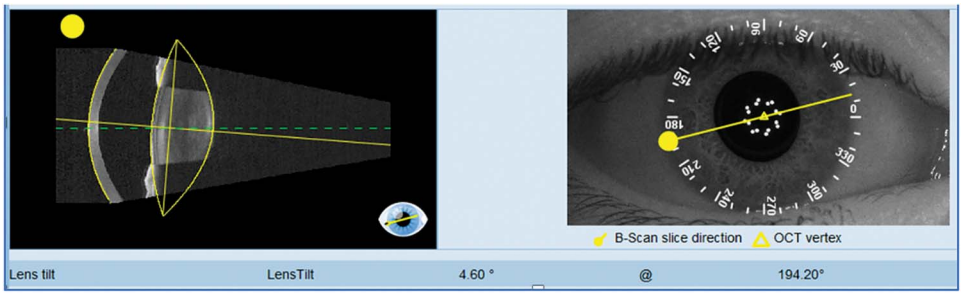

Figure 3. Crystalline lens tilt displayed on the Eyestar 900 SS-OCT device.

Lens Tilt

Lens tilt, either from crystalline lenses or IOLs, has also been shown to induce significant refractive astigmatism.[43] The visual axis is nominally 5 degrees relative to the optical axis of the eye.[44] This is called angle alpha and is due to the temporal displacement of the fovea. This induces around 5 degrees of tilt of the cornea, crystalline lens, and IOL around the vertical axis, with the nasal edge anterior to the temporal edge (Figures 3 and 4). This tilt induces ATR refractive astigmatism. Interestingly, the normal WTR astigmatism in the cornea compensates for the ATR astigmatism from the tilt of the cornea and crystalline lens such that 4% of eyes have no measurable astigmatism and 20% to 30% have < 0.50 D.[13] A number of investigators have measured crystalline lens and IOL tilt, and its impact on refractive astigmatism continues to be explored.[43,45,46] The induced astigmatic change increases when toric IOLs aligned at 90 degrees are tilted around the vertical meridian. Conversely, the induced astigmatic change decreases when toric IOLs aligned at 180 degrees are tilted along the vertical meridian.[43] Clearly, this is a factor that must be accounted for in toric IOL planning, either directly or in toric IOL formulas that use postoperative refraction in a regression approach. The retina does not cause astigmatism, as was demonstrated more than 2 decades ago in a retinoscopy study conducted by Flüeler and Guyton.[47]

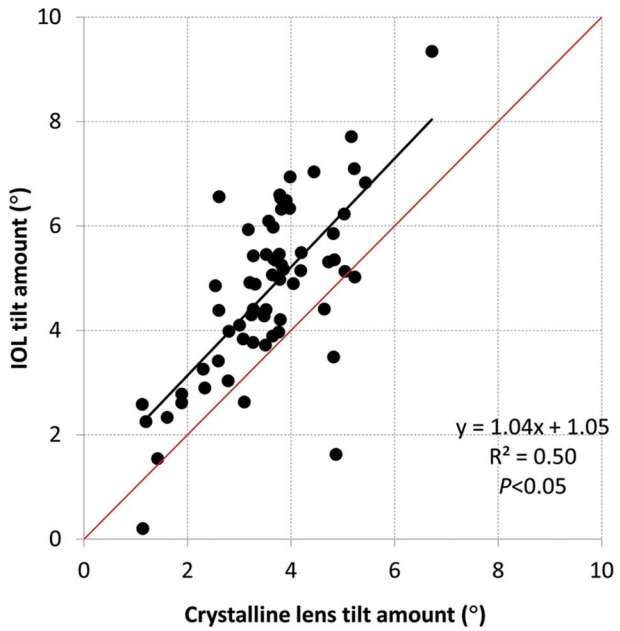

Figure 4. Correlation of tilt magnitude between preoperative crystalline lenses vs postoperative IOLs (correlation coefficient r = 0.707, P < .01) (n = 65 eyes).[44]

REFRACTIVE ASTIGMATISM

Objective vs Subjective Patient Assessment

The accuracy of manifest refraction is limited by the 0.25-D increments of spherical and cylindrical lenses. For measurements of sphere, studies have shown that 2 standard deviations of reproducibility can be as high as ± 0.50 D.[48] High reproducibility in the measurement of the manifest cylinder has been reported in myopic patients examined in a specialized refractive clinic.[49] In addition, these authors noted that the difference in the measured axis among repeated measurements varied inversely with cylinder magnitude. In a pseudophakic population, good agreement was found in astigmatic vectors between subjective refraction, wavefront measurement, and autorefraction, whereas spherical equivalent was found significantly less myopic in the subjective refraction than the 2 other methods.[50] Wavefront technology's ability to incorporate visual quality metrics is a promising advantage of the objective refraction it provides. Two studies have demonstrated that objective refractions from wavefront devices provided equivalent or even better visual performance than the subjective refraction.[51,52]

Influencing Factors

Refractive astigmatism might fluctuate under multiple circumstances, including ocular surface alteration, accommodation state, fatigue, ambient illumination, systemic disorders such as diabetes and uremia, and medications such as topical and oral sulfonamides.[53,54] Cycloplegia has been shown to affect the astigmatism axis, likely because of the crystalline lens tilt about the horizontal axis and to the contribution of the midperipheral cornea.[55,56] Pupil size has also been identified as a critical factor when assessing the impact of astigmatism on uncorrected vision. Larger pupils were shown to be associated with significantly lower optical quality and uncorrected visual acuity performance for the same amount of astigmatism.[4,56,57] Irregular corneas with large amounts of coma, such as can occur in corneas with keratoconus, can be a challenge for obtaining a reliable refraction. The axis and magnitude of refractive astigmatism in eyes with coma-dominant corneal optics have been

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shown to strongly correlate with the meridian and magnitude of coma.

CONCLUSION

A fundamental understanding of ocular astigmatism—its definition, sources, prevalence, and measurement—is essential for both clinical practice and research. With this foundation, the next article will discuss our recommended approaches for analyzing and reporting astigmatic outcomes.

Acknowledgments

In December 2020, the *Journal of Cataract & Refractive Surgery* (JCRS) formed a committee to reach and publish a consensus on clear and accurate astigmatism reporting guidelines to benefit JCRS authors and all researchers. The committee consisted of clinicians and researchers with expertise in this area. Following a series of virtual meetings, several of the committee members prepared the 2 manuscripts, one on background and the second on standards for analyzing astigmatism. In addition to the authors of this paper, we want to acknowledge and thank the other members of the committee who made important contributions to the concepts incorporated in the written result of this project: Graham D. Barrett, MD (Australia); Laure Gobin, PhD (Belgium); and David Smadja, MD (Israel).

WHAT WAS KNOWN

- Astigmatism is the difference between the orthogonal principal planes of minimal and maximal powers of a toric surface, lens, or refraction.
- Corneal astigmatism is a common condition with over 60% of individuals having more than 0.5 diopters of astigmatism.
- With the increase of refractive lens surgeries, both cataract-related and elective, accurately predicting residual refractive astigmatism is more important than ever.
- While several methods that were developed over the past decades for measuring astigmatism are helpful, the lack of consensus on terminology and approach makes effective comparisons difficult.

WHAT THIS PAPER ADDS

- A consistent use of terminology is suggested and provides clear explanations and definitions for measuring astigmatism.
- The integrity of the ocular surface is critically important for accurately measuring corneal astigmatism.
- Clear and accurate astigmatism reporting guidelines based on sound optical principles are provided.

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