

Posterior corneal astigmatism: a review article

This article was published in the following Dove Press journal:
Clinical Optometry

Seyed-Farzad Mohammadi¹
Masoud Khorrami-Nejad^{1,2}
Moein Hamidirad²

¹Translational Ophthalmology Research Center, Farabi Eye Hospital, Tehran University of Medical Sciences, Tehran, Iran; ²School of Rehabilitation, Shahid Beheshti University of Medical Sciences, Tehran, Iran

Abstract: Most human eyes show at least a small degree of corneal astigmatism and it can arise from both surfaces of the cornea. The shape of the anterior corneal surface provides no definitive basis for knowing the toricity of the posterior surface. In the previous studies, average astigmatism of the posterior corneal surface was -0.26 to -0.78 diopter. The radius of the posterior corneal surface is less than the radius of the anterior corneal surface. Most studies have found a clear correlation between the anterior and posterior corneal asphericities and the asphericity of the posterior surface is independent of the vertex radius of curvature, refractive error and gender. In contrast to the anterior corneal surface, the asphericity of the posterior corneal surface varies significantly between meridians. The anterior and posterior corneal surface would have approximately parallel principal meridians and both of these surfaces are often flatter in the horizontal meridian than the vertical one. This is especially true in the higher degrees of corneal astigmatism, and then about 10% of any anterior corneal astigmatism is neutralized by an astigmatism arising from the posterior corneal surface. Although the second corneal surface only contributes to about 10% of the total refractive power of the eye, a precise knowledge of its morphology is needed for the correct diagnosis and monitoring the corneal diseases or the surgical interventions and in many eyes neglecting the posterior corneal surface measurement may lead to significant deviations from the corneal astigmatism estimation. In this article, we have reviewed the shape and the toricity of the posterior corneal surface and also the effect of age on it. We investigated the contribution of posterior corneal astigmatism to the total corneal astigmatism and evaluated the accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement.

Keywords: cornea, posterior corneal astigmatism, corneal toricity

Introduction

Astigmatism is a prevalent optical disorder that affects different visual functions, for instance, visual acuity and sensitivity to the intensity of darkness and brightness of the contrast. It can cause some problems such as reduced vision, and causing some symptoms for the patients such as epiphora, unilateral diplopia, asthenopia and distortion.¹⁻³ The treatment of astigmatism is more difficult than other types of refractive errors due to making some distortions after correction.⁴ These problems are posing a challenge for the patient and the physician.^{3,5} Some studies have shown that age, sex, environment and genetic factors are important points that affect type and amount of astigmatism.^{3,6} Studies estimated that the prevalence of astigmatism is 10–13 percent of the refractive errors.^{3,7}

The optical surface of the cornea is the first and the most important optical surface of the eye and its center thickness is about 550 μm , its vertical diameter is about 11.5 mm and its horizontal diameter is 12.5 mm.⁸ Due to the fact that there is a significant difference between the refractive index of the air and the anterior surface of the cornea, in comparison to the other optical surfaces, the greatest proportion of the dioptric power

Correspondence: Masoud Khorrami-Nejad
School of Rehabilitation, Shahid Beheshti University of Medical Sciences, Damavand Street, Tehran, Iran
Tel +98 217 754 2057
Email op_khorrami@yahoo.com

of the eye has been allocated to it. Totally, the power of the cornea is 43 diopter which is about 2/3 total dioptric power of the eye. This power is lower in the peripheral part in comparison with the center and it is optically an aspheric surface. The posterior corneal radius is 6.5 mm on average that is lower than the anterior corneal radius which is 7.8 mm.^{8,9}

Astigmatism occurs when our visual system does not have a good perception of a point from a point source due to the fact that there are different powers in the different meridians of the cornea. Total corneal astigmatism is made by both the anterior corneal surface and the posterior corneal surface. Due to the point that there is a significant difference between the refractive indices of the anterior corneal surface and the air, anterior corneal astigmatism is much greater than the posterior corneal astigmatism (there is a minute difference between the refractive index of the posterior corneal surface and the aqueous humor; this would impose some limits for the posterior corneal astigmatism). In essence, anterior corneal astigmatism plays the more prominent role in comparison with the posterior corneal astigmatism but we should not turn a blind eye to the effect of the posterior corneal astigmatism.^{10,11}

The criteria that were taken into consideration for this study were having at least one of the keywords and a good relation with this subject of the article (between 1980 and 2019). PubMed's articles were our first priority and in case of repetition with the published article in scientific publication, the priority was given to the article that had the higher impact factor. The exclusion criteria were repetition and irrelevance. The purpose of this study is the review of the posterior corneal astigmatism.

Different classifications of astigmatism

Astigmatism is classified in different ways and diagnosing the type of astigmatism is the most important point that should be taken into consideration before trying to correct it.¹² Totally, it is classified into two main groups that are known as regular and irregular.¹³ In the regular astigmatism, there is 90-degree difference between the steepest and the flattest meridian and it is classified into different groups: simple myopic astigmatism, compound myopic astigmatism, simple hyperopic astigmatism, compound hyperopic astigmatism and finally mixed astigmatism in which one meridian is focused in front of the retina and the other behind the retina. In the irregular astigmatism, the difference between the steepest and flattest meridian is lower than 90 degrees and usually this is because of the

irregularity and non-uniformity of the anterior and posterior corneal surface in which, we cannot create a clear image on the retina just by simple cylinder correction in one specific meridian.^{8,14}

On the other hand, we can classify astigmatism into: 1. corneal, 2. lenticular and 3. total. Astigmatism may occur because of the toricity of the cornea that is calculated through keratometry (corneal astigmatism) or it maybe due to the crystalline lens (lenticular astigmatism). The sum of both the corneal and lenticular astigmatism is known as the total astigmatism, which is captured during retinoscopy.⁸

Idiopathic astigmatism occurs because of the abnormalities that exist through the optical system of the eye in which the most prevalent cause is the anterior and posterior corneal surface.¹⁵ On average, there is 0.50 to 0.75 difference between the principal meridians of the cornea on the anterior surface and the posterior corneal surface is vectorially added to those of the anterior surface to yield the total amount of corneal astigmatism.^{16,17} In the past, keratometry was used and anterior corneal astigmatism was measured and the result was known as the total amount of astigmatism. This was due to the fact that we had limitations when we wanted to measure the exact amount of lenticular astigmatism. Measuring the toricity of the posterior corneal surface is clinically difficult and in normal population, it has a low share in the total astigmatism so that it is generally neglected.¹⁸

When it is talked about the origin of an astigmatism, definitely the crystalline lens should not be forgotten. In the crystalline lens, horizontal radius is steeper than the vertical one. Furthermore, cortical lamella is mostly not concentric so it makes some different refractive indexes in the different meridians of the crystalline lens.^{16,19} Astigmatisms that are iatrogenic or related to some illnesses usually have a greater dioptric power and are more irregular. Corneal scars, keratoconus, different operations and corneal transplants, crystalline lens dislocation and large incisions in the cataract surgery can all cause astigmatism.^{20,21}

Corneal astigmatism

Cornea is a transparent avascular tissue that is responsible for the 2/3 dioptric refractive power of the normal human eye. Moreover, cornea is the main source of astigmatism in the optical system.^{13,22} Total corneal stigmatism is due to the anterior and posterior surface and it occurs when the shape of the cornea is toroidal.²³ Launching an investigation into the optical calculation on the Gullstrand's schematic eye is really helpful in the perception of the real origin of the astigmatism.²⁴

In this model, in order to make an astigmatism, we assume that the radius of curvature in the horizontal meridian of the anterior corneal surface is 7.70 mm and the radius of curvature in the vertical meridian is 10 percent lower (6.93 mm), so the radius of curvature in the vertical meridian of the anterior surface is steeper and thus creating more power in this meridian and finally it causes anterior corneal astigmatism that is with the rule and its amount is 5.42 diopter. According to the power of the principal meridian on the posterior surface, the amount of astigmatism is -0.65 diopter that is against the rule. If we neglect the corneal thickness and presume that the cornea is a thin surface, then total corneal astigmatism is sum of the two corneal surfaces so that the total astigmatism is 4.77 diopter and with the rule.

According to the calculations that were pointed out, if we presume that the radius of curvature in one of the principal meridians of the two surfaces is equal to the average population and the other is 10% lower, then the total astigmatism is lower than the anterior corneal astigmatism and approximately 88% of the anterior corneal astigmatism is equal to the total astigmatism so the posterior corneal astigmatism will nearly counteract 10–12 percent of the anterior corneal astigmatism.^{25–28}

When a RGP lens with a posterior spherical surface is worn in this eye, the anterior tear layer follows the posterior spherical surface of the RGP lens and the posterior tear layer would have the shape of the toroidal cornea and the torical shape of the anterior cornea causes the tear layer lie on the cornea in a torical shape, so if we want to presume that the tear layer has a role in counteracting corneal astigmatism, definitely this is due to the posterior tear interface. If you compare an against-the-rule cylinder that is made by the posterior tear surface (4.8484) with the rule cylinder that is made by the anterior corneal surface (5.4256), it will be shown that the tear layer cannot counteract all astigmatism that is made by the anterior corneal surface and 0.57 diopter of an uncorrected cylinder of the anterior corneal surface still remains. This means that 89% of the anterior corneal astigmatism is counteracted due to using spherical RGP. Moreover, as it was pointed out, posterior corneal astigmatism can counteract 10–12 percent of anterior corneal astigmatism.^{29–34}

So, nearly total amount with the rule astigmatism that is made by the anterior surface will be corrected by an against-the-rule astigmatism which is made by the posterior tear layer surface and the posterior corneal surface; in this way, corneal astigmatism is counteracted by using spherical RGP contact lens. Another important point that

should be taken into consideration is that, the principal meridians of the two corneal surfaces are not always parallel and moreover, this counteraction of the anterior corneal astigmatism is not at all related to the refractive index of the RGP lens and any amount of astigmatism that is related to the crystalline lens is remained uncorrected. According to this theory, every degree of corneal astigmatism could be counteracted by fitting a spherical GP. However, when the corneal astigmatism is 2.50 diopter or more, in order to have a proper and comfortable fit, a back surface toric RGP is needed, because in fitting RGP lens, the point is not just about counteracting an astigmatism and in addition to a good vision, we should consider the ease of the patient and its physiological processes.^{35,36}

An amount of astigmatism that is counteracted by a RGP lens, in addition to the power of the tear layer behind the lens, is dependent on the anterior corneal power. If we divide the refractive index of the tear layer by the refractive index of the cornea ($n_{\text{tear}}/n_{\text{cornea}}: 1.336/1.376=0.89$), we can conclude that 89% of the anterior corneal astigmatism is counteracted by the tear layer that is located behind the RGP lens and 11% of the remained anterior corneal astigmatism could be corrected by the posterior corneal surface.^{16,37–41}

Many surveys have shown that corneal astigmatism is compensated by the optics of the eye. The results of these surveys match with the research conducted by Shankar and Bibber about the relationship between the corneal and refractive astigmatism for 12 people. In this research, it was pointed out that the amounts of refractive and corneal astigmatism were higher in the astigmatic group and in the high corneal astigmatism there would be no compensation in the lens.⁴² Bernen and McKendrick by using vector analysis mentioned that there is a little relationship between the corneal and refractive astigmatism but Kelly and her colleagues emphasized on the relation between the corneal and refractive astigmatism. Moreover, in another research carried out by Huynh and his colleagues they pointed out that there is a relation between corneal, refractive and lenticular astigmatism and their compensation during emmetropization.^{43,44} Other studies have shown that there is a linear relationship between the corneal and refractive astigmatism.^{39,45,48,47}

The result of Liu and his colleague's research specified the fact that during aging, the corneal changes are reflected on the refractive astigmatism but lens' opacity has a little effect on the total astigmatism.⁴⁸ The reason for different results in various studies was due to measuring astigmatism with different instruments, way of choosing and patient

referral, different ages of patients for examination, different classifications of refractive errors, methodologies, types of studies and different analysis by researchers. In the past, because of some limits on the technology that we had, it was not possible to directly measure the posterior corneal astigmatism and usually corneal power and astigmatism were measured only just by the data from the anterior corneal surface and they presumed that the parameters of the posterior corneal surface can be derived by a constant ratio. In some instruments such as handheld and auto keratometer and corneal topography that all just analyze the cornea based on the placido disk, a constant and standard refractive index (mostly $n=1.337$) is used in order to convert the calculation of the anterior corneal surface to the total corneal power and the total corneal astigmatism.¹⁸ The keratometric index was developed so that it could measure the total corneal power without considering the data from the posterior corneal surface and just by recording the findings of the anterior corneal surface. If one wants to use keratometric index, then with the rule astigmatism, the estimation of total corneal astigmatism is higher and against the role astigmatism, it is lower.^{8,14,49}

Measuring corneal astigmatism

For many medical purposes and diagnosis in ophthalmology, the cornea should be evaluated completely and accurately. One of the quantitative parameters of the corneal evaluation is measuring its highest and lowest power. If the cornea is normal, for many medical purposes, the anterior surface keratometry is sufficient. For evaluating the power of the cornea, many different instruments such as different keratometers, topographers, and tomographers have all been produced. Keratometers, which are known as the first instruments for corneal evaluation are based on some assumptions that one may find the correct measurements only in those patients who have normal cornea, so in other patients who have corneal diseases or refractive surgery, their result could be incorrect. Keratoscope is also based on the same principles; they have errors and the physician might make mistakes in the diagnosis and the treatment of the disease. Nowadays, different instruments are available for measuring astigmatism, for instance, instruments for refraction, manual and auto keratometer and some new types of corneal topographies and different types of corneal surface imaging techniques such as Scheimpflug images, Ray tracing and OCT (optical coherence tomography). The amount of astigmatism that is calculated with different instruments is not exactly the

same; so choosing and measuring the exact amount of astigmatism is still a challenge. In some studies, that was done on accuracy of the auto keratometer; it was pointed out that it was roughly reliable in terms of determining the axis but the total power of the cornea was a little bit lower than the measured power by corneal topographers.^{50,53-59}

Different studies have shown the specific relation between the shape of the anterior and posterior corneal surface in the normal human eye.^{58,61,62,63,59} In some other instruments such as manual and auto keratometer and corneal topography that all analyze the cornea based on the placido disk, a constant and standard refractive index (1.337 at most of the instruments) is used for converting the calculation of the anterior corneal surface into the total power and the total corneal astigmatism; however, these days newer technology such as OCT and Scheimpflug device can be used for measuring the parameters of the posterior corneal surface directly. The toricity of the posterior cornea is calculated in different ways, such as Purkinje images, Scheimpflug photography and Slit scan images.^{8,14,17,35,37,60,61,66-72}

Pentacam Scheimpflug imaging system (Oculus) not only captures an accurate image of the cornea but also interpret the different parts of the anterior segment's features.^{69,70} Dual Scheimpflug analyzer is another instrument for measuring the parameters of the cornea. This device combines and unifies the data from the Placido disk and Scheimpflug in a particular way, in order to calculate the numerical values of the anterior corneal surface; however, for checking the information of the posterior corneal surface, just Scheimpflug data are used. The other important point that should be taken into consideration is the fact that, for checking the exact asphericity of the posterior corneal surface, in addition to the Purkinje images, the data from the videokeratoscopy and the pachymetry (for measuring the corneal thickness) should be used.^{71,72}

Something that is visible on the ruler of the hand-held keratometer, in addition to the radius of curvature of the anterior corneal surface, is the total power of the cornea. Both the anterior and posterior surface have a prominent role in specifying the total corneal power. In order to understand the fact how the keratometers are calibrated for measuring the total corneal power without surveying the posterior corneal surface.^{35,73-75} Particularly, the correctness of this claim that the parallelism of the principal meridians of the anterior and posterior surface in people who have high amount of astigmatism is almost definite and if the keratometer just wants to estimate the total corneal power without evaluating the posterior corneal

surface and just by the information of the anterior corneal surface, the refractive index of the cornea should be changed; this means that instead of using 1.376, we can use 1.3375. By using the lower refractive index for the cornea in the keratometer, an amount of the calculated power is nearer to the total corneal power in comparison with the anterior surface.^{76,81,82,79}

If we want to accept this algorithm, we should presume that there is a direct and linear relation between the curvature of the anterior and posterior corneal surface and the radius of curvature of the anterior cornea to the radius of curvature of the posterior cornea (AP ratio) has defined this point. In the schematic eyes, AP ratio is set between 1.2 and 1.32. AP ratio has been studied in the human eye in different surveys. These studies have used some special techniques, for instance, Slit lamp photography, Purkinje images, Pachymetry, Photokeratoscopy, Corneal topography, Scheimpflug photography and Slit scan topography. The average of the AP ratio in the human eye is between 1.177 and 1.235. This constant ratio between the radius of curvature of the anterior and posterior corneal surfaces which has been obtained in different studies is used in determining the optimum refractive index of the keratometer.^{17,80,85,86,83}

One of the hypotheses of the keratometer is using the refractive index of 1.3375 for the cornea that is based on this fact that the ratio of the posterior corneal radius of curvature to its anterior is 0.883, while the refractive index of the cornea is 1.376 which shows why the power of the posterior surface is negative.⁸⁴ This discrepancy in the normal eyes will make some minor faults that can be neglected, but for the eyes that have diseases or a history of refractive surgeries, using this refractive index (1.3375) will make some mistakes that will sometimes overcorrect the result of the surgery; hence, in order to compensate this mistake, the anterior and posterior surface and their power should be evaluated separately and then the total power be calculated; so in order to reach this goal, the topographic technology that can evaluate the posterior corneal surface such as dual Scheimpflug camera technology or Slitscan could be used.^{85,90,87} However, in some researches, the refractive index that is presumed in the keratometer is different in comparison with the number that is used these days; for example, in a survey that was done by Doobleman and his colleagues in 2006 about the features of the anterior and posterior corneal surface in 114 normal people, the average of the radius of curvature of the posterior surface is 6.53 ± 0.25 , the average of the radius of

curvature of the anterior surface is 7.79 ± 0.27 ; hence, the posterior corneal astigmatism is 0.3 and anterior surface is 0.99 such that both of them were flatter on the horizontal meridian than vertical one. The results showed that it is better to use the refractive index of 1.329 instead of 1.3375 (that is used by default in many keratometers) which is lower than the present amount.

The topographical system of the Orbscan (Bausch & Lomb, USA) makes a good topographic image of both the anterior and posterior surface; moreover, it can calculate the corneal thickness accurately. This device has made it possible for us to increase the level of our knowledge about the shape and the function of normal and diseased cornea. Orbscan can measure many points (up to 9000 points) at both the anterior and posterior corneal surface in a short period of time (1.5 sec). However, it is sometimes not very accurate to measure the parameters of the posterior corneal surface especially after refractive surgeries. Pentacam uses dual Scheimpflug camera for capturing an image of the anterior part of the eye and it can also take some images, for instance, elevation maps of both corneal surfaces, pachymetry maps and biometric measurements of the anterior parts of the eye; this device can collect data from 2500 points in less than 2 seconds.^{88,93,90}

Here, we have 4 groups of corneal measurements:

1. Corneal astigmatism that is calculated by the total power. In this method for calculating corneal astigmatism, the data from the anterior and posterior surface.
2. Corneal astigmatism that is calculated by the Sim-K: in this method, corneal astigmatism is calculated by the data from keratometry in 1–4 mm of the central cornea and the total astigmatism which is the difference between the steepest and the flattest meridian, measured by keratometry and in line with the steep meridian. Obviously, in this method, all of the collected data are based on the keratometric measurements of the anterior corneal surface and corneal astigmatism is calculated by defining a refractive index for keratometer, based on the collected data.
3. Anterior corneal astigmatism: In this method, anterior corneal astigmatism is calculated by the data from the anterior corneal surface.
4. Posterior corneal astigmatism: In this method, posterior corneal astigmatism is calculated by the data from the 1–4 mm central part of the posterior

corneal surface. The refractive index of the cornea is 1.376 and the refractive index of the aqueous humor is 1.336.

Amount of posterior corneal astigmatism

In the studies that have been done about this topic, it was reported that an amount of this astigmatism is -0.26 to -0.76 diopter.^{11,91,92} In an extensive research that was done by Douglas and his colleagues in 2003 on 715 people, ranging from 20 to 89 years old, an average amount of astigmatism was 0.3 diopter; in this study, in order to measure an amount of astigmatism, both corneal surfaces were considered. Optically, the power of an optical surface has a linear relation with the refractive index of its surrounding environment; and the greater the difference between these two environments, the greater the power at the optical surface; hence, the little difference between the refractive indices of the aqueous and the cornea is the main reason that why an amount of posterior corneal astigmatism is insignificant. However, the toricity of the posterior corneal surface is more than its anterior one. In addition to this, the posterior surface is steeper than the anterior one, despite the lower radius of curvature.^{20,93}

Evaluation of the posterior corneal astigmatism to the total astigmatism

It is obvious that the total corneal astigmatism is measured by the sum of anterior and posterior surfaces. On average, an amount of astigmatism that is seen on the posterior surface is lower than the anterior one; and its type of astigmatism is usually the opposite of what is seen on the anterior surface, because most of the principal meridians are parallel on the two corneal surfaces. The reason for this point that types of corneal astigmatism are reversed on the two surfaces is due to the negative power of the posterior corneal surface, despite the parallel meridians. This topic is so evident especially when a person has a higher amount of astigmatism; therefore, an astigmatism of the posterior corneal surface neutralizes part of an astigmatism of the anterior corneal surface. As we know the posterior corneal surface has a negative dioptric power, the steeper curve in the vertical meridian will make an ATR astigmatism, so mostly the calculated total corneal power (in which the posterior corneal astigmatism is also calculated) will show lower amount of with-the-rule astigmatism in comparison with the point that when the corneal astigmatism is

measured based on the information of the anterior corneal surface alone. Vector analysis can be used in order to find out the errors, resulted from the calculation of total astigmatism just by using the anterior corneal power.^{8,61,92,94,95}

The relation between the anterior and posterior corneal astigmatism

So far, several groups of researchers have been working on the relation between the two corneal surfaces.^{11,13,35,39,48,59,93,96-99,101-111} They have shown that, when the steepest meridian of the anterior corneal surface is vertical or nearly vertical, there is a direct correlation between an amount of corneal astigmatism on both the anterior and posterior surface, but when the steepest meridian of the anterior corneal surface is oblique, the intensity of this correlation is reduced so that there would be no relationship between the corneal astigmatism of the anterior and posterior corneal surface in the eyes that the steepest meridian of the anterior corneal surface is horizontal. However, clinically the changes of the posterior corneal astigmatism play an important role at most of these groups. In the other study that was surveyed by Dubbelman and his colleagues in 2007 on the relationship between the two corneal surfaces, it was understood that there was a strong relation between the shapes of the two corneal surfaces in normal population.¹⁵ Some studies have found a correlation between an asphericity of both the anterior and posterior surface in the vertical meridian; in contrast, other studies found no correlation between the asphericity of the surfaces. What is clear right now is the point that we cannot evaluate asphericity of the posterior corneal surface just by the shape of the anterior surface.

Effect of increasing age on the anterior and posterior corneal astigmatism

Increasing age mostly affects astigmatism of the anterior corneal surface and posterior corneal surface is less affected by the age. By increasing age, the steep meridian of the anterior corneal surface tends to change its direction from vertical to horizontal, while these changes did not reported in the steep meridian of the posterior corneal surface.^{8,14,17} Since the prevalence of with-the-rule astigmatism is higher in the youth and by increasing age it tends to change to against-the-rule astigmatism, the posterior corneal astigmatism acts relatively as a compensating factor for anterior

corneal astigmatism in the young people (the steep meridian is vertical). However, in the older population, the posterior corneal astigmatism has a boosting effect and increases the anterior corneal astigmatism (the steep meridian is horizontal). Actually, the posterior corneal astigmatism will compensate the anterior corneal astigmatism in the younger population and increases the total astigmatism in the older population.^{35,48,108,113,110} Finally, knowing about the changes of the corneal shape with increasing age is very important because these changes can affect the stability of the corneal shape after refractive surgery.^{111,116,113}

The effect of posterior corneal astigmatism on eye surgeries

Accurate screening before surgery is one of the key factors in the success of the refractive surgery that would reduce the unpleasant results and patient dissatisfactions.^{91–116} In the past, the classical screening method was used for the patients who were candidate for refractive surgery; it included corneal topography based on placido disk (evaluation of the anterior corneal surface) and measuring the corneal thickness.^{116,117} Due to the fact that corneal topography plays a prominent role and has been a great revolution in diagnosing and managing corneal diseases, it has a leading role by surveying the results of the corneal refractive surgery and treating its complications after that.^{91,117,118}

There are two important points that should be taken into consideration about posterior corneal astigmatism; firstly, we cannot definitely determine an amount of posterior astigmatism based on the information of the anterior corneal surface and secondly, posterior corneal astigmatism can affect the results of refractive surgeries for correcting astigmatism, if they are only based on the information of the anterior corneal surface.^{91,119,120,123–127} For instance, failure in calculating an amount of posterior corneal astigmatism with a steep meridian (that can cause against the rule astigmatism at the posterior corneal surface) can cause more correction for the eyes that have with-the-rule astigmatism or less correction for the eyes that have against-the-rule astigmatism.

Posterior corneal astigmatism and cataract surgery

Significant corneal astigmatism is observed in 14% of the society. Using spectacles in high astigmatism has some limitations because of inducing meridional magnification; therefore, these days, for those who have cataract surgeries, there is a tendency for correcting the astigmatism and reducing

distortions at the time of surgery. These methods are very useful in patients who have an astigmatism 2 or more diopters.¹²⁶ In the latest methods of cataract surgery, despite the recent developments, lens extraction without any possible harm and reducing the need for using spectacles after surgery is still challenging. In order to achieve this goal, it is very important to consider all of the refractive errors especially astigmatism at the time of the surgery. Due to the fact that there are new technologies for this surgery and new formulas are used to measure intra ocular lens power, spherical errors after surgery have greatly reduced. In spite of this, 20% of these people who have cataract have a corneal astigmatism that is more than 1.50 diopter before surgery.^{127,128} In the people who have cataract surgery, failure to estimate an exact amount of astigmatism by neglecting the posterior astigmatism can cause some errors in correcting an astigmatism and due to the point that most of the eyes have a posterior astigmatism, which is ATR, if this negligence occurs in toric intra ocular lens use, it overcorrects WTR astigmatism and undercorrects ATR astigmatism. Controlling this astigmatism is vital for the best outcome.

During recent years, correction of the astigmatism is one of the main goals in the cataract surgery and this strong tendency is increasing during phacoemulsification by having small incision and using foldable lenses in order to correct both spherical and cylindrical refractive errors.¹²⁸ For correcting an astigmatism in these cases, many different techniques are used; for instance, changing the size and the location of the incision,¹²⁹ using a loose incision in the cornea or limbus,¹³⁰ using clear corneal incisions anteriorly at steeper meridians,¹³¹ using toric intra ocular lenses,^{132,133} and Excimer laser.¹³⁴ The main purpose of using these methods is correcting the astigmatism as much as possible, in order to make an appropriate and a satisfactory uncorrected visual acuity (UCVA).

The people who have cataract, after surgery, expect to have a clear vision and reduce their dependency on spectacles. In the cataract surgery, because small incisions and foldable lenses are used, most of the patients will be emmetropic.^{132–136} There are different methods for reducing an astigmatism during the cataract surgery. Using an incision in the steepest meridian is the first suggestion.¹²⁶ In the different studies, an amount of astigmatic correction with this method is definite but it is usually lower than 1.00 diopter, also having some incisions at some meridians are technically hard or impossible.¹³⁶ The other method is astigmatic keratotomy that because of the incisions which are so close to the center of the cornea, the feeling of scattering, irregular astigmatism, diplopia, fluctuation in

refractive errors and the need for pachymetry and diamond knife has some complications and limitations.^{137,138}

Limbal relaxing incision (LRI)¹³⁷ is another method for reducing an astigmatism during the cataract surgery that has some advantages, for instance, simplicity of this method, little discomfort for the patient, early stability due to the location of the incision at the limbus area and no change in corneal spherical equivalent (SE) because of 1:1 coupling effect (if two incisions are used); but it has some limitations because of the need for pachymetry, using diamond knife and the different views about using nomogram.^{130,139} Gills and his colleagues' studies showed that this method was useful for astigmatism that are between 2.00 and 5.00 diopters and had some benefits such as keeping the optical quality of the cornea, reducing the risk of diffraction and earlier improvement of vision after surgery.¹⁴⁰

Implanting toric IOL is another method for reducing astigmatism that will make a good vision after surgery but these lenses are expensive and implanting these lenses require skill and knowledge and one of the complications of using these lenses is rotation after surgery, which is still a basic problem. Manifest astigmatism following toric IOL implantation can be reduced by proper attention to both corneal surfaces. In toric IOL calculations, the methods that take the effect of the posterior corneal astigmatism into account are recommended.^{132,133,141}

Excimer laser can be used to correct the remained or induced astigmatism after cataract surgery. There are some points that should be taken into consideration: the high price of this method, limited availability of the laser centers, complications of Excimer laser, for example, reducing BCVA, flap complications, night vision problems and regressions.^{134,142}

In 2000, for the first time, Lever and et al used a couple clear corneal incision corresponding to the steep meridian or OCCI (opposite clear corneal incision) in order to reduce corneal astigmatism.¹³¹ This is an easy method that does not need any extra tools and easy to learn, therefore, it does impose more costs to the patients. This method is effective for correcting mild to moderate corneal astigmatism. With this method, an average astigmatic reduction for 3–5 mm incision is 0.5 to 2 D.^{143,144} For higher amount of astigmatism, using other methods or a mix of some methods are advised.¹⁴⁵

In some studies, it is suggested that for increasing the effect of clear corneal incision at the opposite steep meridian, a bigger incision is needed in addition to temporary sutures for closing the wound. The disadvantages of these methods are: increasing the risk of endophthalmitis because

of its penetrating feature in comparison with the other non-penetrating methods and in case of having a leakage, a nylon suture can be used to close the wound.^{15,131,146–150}

Disclosure

The authors report no conflicts of interest in this work.

References

- Pascolini D, Mariotti SP. Global estimates of visual impairment: 2010. *Br J Physiol Opt.* 2012;96(5):614–618. doi:10.1136/bjophthalmol-2011-300539
- Rashad KM. Laser in situ keratomileusis for myopic astigmatism. *J Refract Surg.* 1999;15(6):653–660.
- Read SA, Collins MJ, Carney LG. A review of astigmatism and its possible genesis. *Clin Exp Optom.* 2007;90(1):5–19. doi:10.1111/j.1444-0938.2007.00112.x
- Hashemi H, Khabazkhoob M, Peyman A, et al. The association between residual astigmatism and refractive errors in a population-based study. *J Refract Surg.* 2013;29(9):624–628. doi:10.3928/1081597X-20130620-01
- Baude D, Chavel P, Joyeux D, Taboury J, inventors; Essilor International (Cie Generale d Optique) SA, assignee. Optical lens for correcting astigmatism. United States patent US 5,016,977. 1991 May 21.
- Fritsche LG, Chen W, Schu M, et al. Seven new loci associated with age-related macular degeneration. *Nat Genet.* 2013;45(4):433. doi:10.1038/ng.2578
- Parrey MU, Elmorsy E. Prevalence and pattern of refractive errors among Saudi adults. *Pakistan J Med Sci.* 2019;35(2):394. doi:10.12669/pjms.35.2.648
- Koch DD, Ali SF, Weikert MP, Shirayama M, Jenkins R, Wang L. Contribution of posterior corneal astigmatism to total corneal astigmatism. *J Cataract Refract Surg.* 2012;38(12):2080–2087. doi:10.1016/j.jcrs.2012.08.036
- Wojciechowski R. Nature and nurture: the complex genetics of myopia and refractive error. *Clin Genet.* 2011;79(4):301–320. doi:10.1111/j.1399-0004.2010.01592.x
- Cheng LS, Tsai CY, Tsai RJF, Liou SW, Ho JD. Estimation accuracy of surgically induced astigmatism on the cornea when neglecting the posterior corneal surface measurement. *Acta Ophthalmol (Copenh).* 2011;89(5):417–422. doi:10.1111/j.1755-3768.2009.01732.x
- Lowry EA, Li J, Kasi SK, et al. The effect of anterior corneal astigmatism orientation on toric intraocular lens outcomes. *Open J Ophthalmol.* 2019;9(2):84–93. doi:10.4236/ojoph.2019.92010
- Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *lancet.* 1986;1(8476):307–310.
- Sinjab MM. Introduction to Astigmatism and Corneal Irregularities. In: Sinjab M, Cummings A, editors. *Customized Laser Vision Correction.* New York: Springer; 2018:1–64.
- Ho J-D, Liou S-W, Tsai RJ-F, Tsai C-Y. Effects of aging on anterior and posterior corneal astigmatism. *Cornea.* 2010;29(6):632–637. doi:10.1097/ICO.0b013e3181c2965f
- Dubbelman M, Sicam VAD, Van der Heijde RG. The contribution of the posterior surface to the coma aberration of the human cornea. *J Vis.* 2007;7(7):10. doi:10.1167/7.7.10
- Dunne MC, Royston JM, Barnes DA. Normal variations of the posterior corneal surface. *Acta Ophthalmol (Copenh).* 1992;70(2):255–261.
- Ho J-D, Tsai C-Y, Liou S-W. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement. *Am J Ophthalmol.* 2009;147(5):788–795. doi:10.1016/j.ajo.2008.12.020

18. Olsen T. On the calculation of power from curvature of the cornea. *Br J Physiol Opt*. 1986;70(2):152–154. doi:10.1136/bjo.70.2.152
19. Chang YC, Mesquita GM, Williams S, et al. In vivo measurement of the human crystalline lens equivalent refractive index using extended-depth OCT. *Biomed Opt Express*. 2019;10(2):411–422. doi:10.1364/BOE.10.000411
20. Edmund C. Posterior corneal curvature and its influence on corneal dioptric power. *Acta Ophthalmol (Copenh)*. 1994;72(6):715–720.
21. Keirl A, Christie C. *Clinical Optics and Refraction: A Guide for Optometrists, Contact Lens Opticians and Dispensing Opticians*. Amsterdam: Elsevier Health Sciences; 2007.
22. Patel S, Marshall J, Fitzke FW. Refractive index of the human corneal epithelium and stroma. *J Refract Surg*. 1995;11(2):100–105.
23. Ophthalmology AAo. *Basic and Clinical Science Course 2007–2008: Section:8 External Disease and Cornea*. San Francisco, CA: American Academy of Ophthalmology; 2007.
24. Silva D, Mota M, Pedrosa C, et al. Posterior corneal astigmatism modifications after cataract surgery and its role on total corneal astigmatism. *Ann Eye Sci*. 2018;3(7). doi:10.21037/aes.2018.07.01
25. Born ME. Wolf principles of optics. *Pergamon Press*. 1980;6:188–189.
26. Illueca C, Mas D, Perez J, Pons AM, Artigas JM. Refractive analysis of the human cornea through propagated fields. *J Mod Opt*. 2001;48(5):811–829. doi:10.1080/09500340108230954
27. Pérez J, Mas D, Illueca* C, Miret JJ, Vázquez C, Hernández C. Complete algorithm for the calculation light patterns inside the ocular media. *J Mod Opt*. 2005;52(8):1161–1176. doi:10.1080/09500340512331327598
28. Pérez J, Mas D, Miret JJ, Vázquez C, Hernández C, Illueca C. Fresnel-based analysis of Kasprzak's crystalline model: statistical results and individual predictions. *Opt Int J Light Electron Optics*. 2005;116(2):49–57. doi:10.1016/j.ijleo.2004.11.003
29. Goodman JW. *Introduction to Fourier Optics*. Greenwood Village, CO: Roberts and Company Publishers; 2005.
30. Guirao A, Artal P. Corneal wave aberration from videokeratography: accuracy and limitations of the procedure. *J Opt Soc Am A Opt Image Sci Vis*. 2000;17(6):955–965.
31. Kiely PM, Smith G, Carney LG. The mean shape of the human cornea. *Opt Acta (Lond)*. 1982;29(8):1027–1040. doi:10.1080/713820960
32. Hernández-Verdejo JL, Arrubarrena C, Cañones R, Mikropoulos DG, Teus MA. Posterior corneal astigmatism and efficacy in refractive correction. *J Refract Surg*. 2018;34(4):286–287. doi:10.3928/1081597X-20180214-03
33. Mas D, Garcia J, Ferreira C, Bernardo LM, Marinho F. Fast algorithms for free-space diffraction patterns calculation. *Opt Commun*. 1999;164(4–6):233–245. doi:10.1016/S0030-4018(99)00201-1
34. Smith G, Atchison DA. Equivalent power of the crystalline lens of the human eye: comparison of methods of calculation. *JOSA A*. 1997;14(10):2537–2546.
35. Dubbelman M, Sicam V, Van der Heijde G. The shape of the anterior and posterior surface of the aging human cornea. *Vision Res*. 2006;46:993–1001. doi:10.1016/j.visres.2005.09.021
36. Mandell RB. Corneal power correction factor for photorefractive keratectomy. *J Refract Surg*. 1994;10(2):125–128.
37. Dubbelman M, Weeber HA, Van Der Heijde RG, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface determined by corrected Scheimpflug photography. *Acta Ophthalmol Scand*. 2002;80(4):379–383.
38. Oshika T, Tomidokoro A, Tsuji H. Regular and irregular refractive powers of the front and back surfaces of the cornea. *Exp Eye Res*. 1998;67(4):443–447. doi:10.1006/exer.1998.0558
39. Remón L, Benlloch J, Furlan WD. Corneal and refractive astigmatism in adults: a power vectors analysis. *Optom Vis Sci*. 2009;86(10):1182–1186. doi:10.1097/OPX.0b013e3181baac2c
40. Dunne MC, Elawad ME, Barnes DA. A study of the axis of orientation of residual astigmatism. *Acta Ophthalmol (Copenh)*. 1994;72(4):483–489.
41. Kelly JE, Mihashi T, Howland HC. Compensation of corneal horizontal/vertical astigmatism, lateral coma, and spherical aberration by internal optics of the eye. *J Vis*. 2004;4(4):2. doi:10.1167/4.4.2
42. Shankar S, Bobier WR. Corneal and lenticular components of total astigmatism in a preschool sample. *Optom Vis Sci*. 2004;81(7):536–542.
43. McKendrick AM, Brennan NA. Distribution of astigmatism in the adult population. *JOSA A*. 1996;13(2):206–214.
44. Huynh SC, Kifley A, Rose KA, Morgan I, Heller GZ, Mitchell P. Astigmatism and its components in 6-year-old children. *Invest Ophthalmol Vis Sci*. 2006;47(1):55–64. doi:10.1167/iov.05-0182
45. Baldwin WR, Mills D. A longitudinal study of corneal astigmatism and total astigmatism. *Am J Optom Physiol Opt*. 1981;58(3):206–211.
46. Grosvenor T, Ratnakaram R. Is the relation between keratometric astigmatism and refractive astigmatism linear? *Optom Vis Sci*. 1990;67(8):606–609.
47. Keller PR, Collins MJ, Carney LG, Davis BA, Van Saarloos PP. The relation between corneal and total astigmatism. *Optom Vis Sci*. 1996;73(2):86–91.
48. Liu Y-C, Chou P, Wojciechowski R, et al. Power vector analysis of refractive, corneal, and internal astigmatism in an elderly Chinese population: the Shihpai eye study. *Invest Ophthalmol Vis Sci*. 2011;52(13):9651–9657. doi:10.1167/iov.11-7641
49. Mohammadi M, Naderan M, Pahlevani R, Jahanrad A. Prevalence of corneal astigmatism before cataract surgery. *Int Ophthalmol*. 2016;36(6):807–817. doi:10.1007/s10792-016-0201-z
50. Bullimore MA, Buehren T, Bissmann W. Agreement between a partial coherence interferometer and 2 manual keratometers. *J Cataract Refract Surg*. 2013;39(10):1550–1560. doi:10.1016/j.jcrs.2013.03.034
51. Chang M, Kang S-Y, Kim HM. Which keratometer is most reliable for correcting astigmatism with toric intraocular lenses? *Korean J Ophthalmol*. 2012;26(1):10–14. doi:10.3341/kjo.2012.26.1.10
52. Crawford AZ, Patel DV, McGhee CN. Comparison and repeatability of keratometric and corneal power measurements obtained by Orbscan ii, Pentacam, and Galilei corneal tomography systems. *Am J Ophthalmol*. 2013;156(1):53–60. doi:10.1016/j.ajo.2013.01.029
53. Kobashi H, Kamiya K, Igarashi A, et al. Comparison of corneal power, corneal astigmatism, and axis location in normal eyes obtained from an autokeratometer and a corneal topographer. *J Cataract Refract Surg*. 2012;38(4):648–654. doi:10.1016/j.jcrs.2011.11.026
54. Shirayama M, Wang L, Weikert MP, Koch DD. Comparison of corneal powers obtained from 4 different devices. *Am J Ophthalmol*. 2009;148(4):528–535.e1. doi:10.1016/j.ajo.2009.04.028
55. Srivannaboon S, Chirapapaisan C, Chonpimai P. Comparison of corneal astigmatism and axis location in cataract patients measured by total corneal power, automated keratometry, and simulated keratometry. *J Cataract Refract Surg*. 2012;38(12):2088–2093. doi:10.1016/j.jcrs.2012.07.024
56. Visser N, Berendschot TT, Verbakel F, de Brabander J, Nuijts RM. Comparability and repeatability of corneal astigmatism measurements using different measurement technologies. *J Cataract Refract Surg*. 2012;38(10):1764–1770. doi:10.1016/j.jcrs.2012.05.036
57. Whang WJ, Byun YS, Joo CK. Comparison of refractive outcomes using five devices for the assessment of preoperative corneal power. *Clin Experiment Ophthalmol*. 2012;40(5):425–432. doi:10.1111/j.1442-9071.2012.02777.x
58. Navarro R, Rozema JJ, Emamian MH, Hashemi H, Fotouhi A. Average biometry of the cornea in a large population of Iranian school children. *JOSA A*. 2019;36(4):85–92. doi:10.1364/JOSAA.36.000B85

59. Schlegel Z, Hoang-Xuan T, Gatinel D. Comparison of and correlation between anterior and posterior corneal elevation maps in normal eyes and keratoconus-suspect eyes. *J Cataract Refract Surg.* 2008;34(5):789–795. doi:10.1016/j.jcrs.2007.12.036
60. Módis L Jr, Langenbucher A, Seitz B. Evaluation of normal corneas using the scanning-slit topography/pachymetry system. *Cornea.* 2004;23(7):689–694.
61. Dunne M, Royston JM, Barnes DA. Posterior corneal surface toricity and total corneal astigmatism. *Optom Vis Sci.* 1991;68(9):708–710.
62. Ho J-D, Tsai C-Y, Tsai RJ-F, Kuo -L-L, Tsai I-L, Liou S-W. Validity of the keratometric index: evaluation by the Pentacam rotating Scheimpflug camera. *J Cataract Refract Surg.* 2008;34(1):137–145. doi:10.1016/j.jcrs.2007.09.033
63. Kawamorita T, Uozato H, Kamiya K, et al. Repeatability, reproducibility, and agreement characteristics of rotating Scheimpflug photography and scanning-slit corneal topography for corneal power measurement. *J Cataract Refract Surg.* 2009;35(1):127–133. doi:10.1016/j.jcrs.2008.10.019
64. Piñero DP, González CS, Alió JL. Intraobserver and interobserver repeatability of curvature and aberrometric measurements of the posterior corneal surface in normal eyes using Scheimpflug photography. *J Cataract Refract Surg.* 2009;35(1):113–120. doi:10.1016/j.jcrs.2008.10.010
65. Prisant O, Hoang-Xuan T, Proano C, Hernandez E, Awad S, Azar DT. Vector summation of anterior and posterior corneal topographical astigmatism. *J Cataract Refract Surg.* 2002;28(9):1636–1643. doi:10.1016/S0886-3350(01)01258-5
66. Royston J, Dunne M, Barnes D. Measurement of posterior corneal surface toricity. *Optom Vis Sci.* 1990;67(10):757–763.
67. Wang L, Mahmoud AM, Anderson BL, Koch DD, Roberts CJ. Total corneal power estimation: ray tracing method versus Gaussian optics formula. *Invest Ophthalmol Vis Sci.* 2011;52(3):1716–1722. doi:10.1167/iovs.09-4982
68. Wang L, Shirayama M, Koch DD. Repeatability of corneal power and wavefront aberration measurements with a dual-scheimpflug placido corneal topographer. *J Cataract Refract Surg.* 2010;36(3):425–430. doi:10.1016/j.jcrs.2009.09.034
69. Shetty R, Arora V, Jayadev C, et al. Repeatability and agreement of three Scheimpflug-based imaging systems for measuring anterior segment parameters in keratoconus. *Invest Ophthalmol Vis Sci.* 2014;55(8):5263–5268.
70. Sinjab MM. *Step by Step®: Reading Pentacam Topography: Basics and Case Study Series.* New Dehli: Jaypee Brothers Medical Publishers; 2015.
71. Holman JP, Gajda WJ. *Experimental Methods for Engineers.* New York: McGraw-Hill; 2001.
72. Oliveira CM, Ribeiro C, Franco S. Corneal imaging with slit-scanning and Scheimpflug imaging techniques. *Clin Exp Optom.* 2011;94(1):33–42. doi:10.1111/j.1444-0938.2010.00509.x
73. Eryildirim A, Ozkan T, Eryildirim S, Kaynak S, Cingil G. Improving estimation of corneal refractive power by measuring the posterior curvature of the cornea. *J Cataract Refract Surg.* 1994;20(2):129–131. doi:10.1016/S0886-3350(13)80151-4
74. Lowe RF, Clark B. Posterior corneal curvature. Correlations in normal eyes and in eyes involved with primary angle-closure glaucoma. *Br J Ophthalmol.* 1973;57(7):464. doi:10.1136/bjo.57.7.464
75. Royston J, Dunne M, Barnes D. Measurement of the posterior corneal radius using slit lamp and Purkinje image techniques. *Ophthalmic Physiol Opt.* 1990;10(4):385–388.
76. Belin MW, Khachikyan SS. An introduction to understanding elevation-based topography: how elevation data are displayed – a review. *Clin Experiment Ophthalmol.* 2009;37(1):14–29. doi:10.1111/j.1442-9071.2008.01821.x
77. Belin MW, Zloty P. Accuracy of the PAR corneal topography system with spatial misalignment. *Clao J.* 1993;19(1):64–68.
78. Klein SA, Mandell RB. Shape and refractive powers in corneal topography. *Invest Ophthalmol Vis Sci.* 1995;36(10):2096–2109.
79. Sicam VAD, Dubbelman M, van der Heijde RG. Spherical aberration of the anterior and posterior surfaces of the human cornea. *JOSA A.* 2006;23(3):544–549.
80. Bennet A, Rabbets R. Retinoscopy (skiascopy). *Clin Visual Optics.* 1989;411:342–344.
81. Liou H-L, Brennan NA. Anatomically accurate, finite model eye for optical modeling. *JOSA A.* 1997;14(8):1684–1695.
82. Fam H-B, Lim K-L. Validity of the keratometric index: large population-based study. *J Cataract Refract Surg.* 2007;33(4):686–691. doi:10.1016/j.jcrs.2006.11.023
83. Olsen GJ, Lane DJ, Giovannoni SJ, Pace NR, Stahl DA. Microbial ecology and evolution: a ribosomal RNA approach. *Annu Rev Microbiol.* 1986;40(1):337–365. doi:10.1146/annurev.mi.40.100186.002005
84. Norrby S. Pentacam keratometry and IOL power calculation. *J Cataract Refract Surg.* 2008;34(1):3. doi:10.1016/j.jcrs.2007.08.015
85. Tang M, Chen A, Li Y, Huang D. Corneal power measurement with Fourier-domain optical coherence tomography. *J Cataract Refract Surg.* 2010;36(12):2115–2122. doi:10.1016/j.jcrs.2010.07.018
86. Sónego-Krone S, López-Moreno G, Beaujon-Balbi OV, Arce CG, Schor P, Campos M. A direct method to measure the power of the central cornea after myopic laser in situ keratomileusis. *Arch Ophthalmol.* 2004;122(2):159–166. doi:10.1001/archoph.122.2.159
87. Srivannaboon S, Reinstein DZ, Sutton HF, Holland SP. Accuracy of Orbscan total optical power maps in detecting refractive change after myopic laser in situ keratomileusis. *J Cataract Refract Surg.* 1999;25(12):1596–1599. doi:10.1016/S0886-3350(99)00286-2
88. Sanhermelando MV, Lleó A, Alonso L, Rahhal MS, et al. Repeatability of central corneal thickness and ocular anterior chamber depth measurements with the Orbscan topography system. *Eur J Anat.* 2019;6(2):59–64.
89. Buehl W, Stojanac D, Sacu S, Drexler W, Findl O. Comparison of three methods of measuring corneal thickness and anterior chamber depth. *Am J Ophthalmol.* 2006;141(1):7–12. doi:10.1016/j.ajo.2005.08.048
90. Lackner B, Schmidinger G, Skorpik C. Validity and repeatability of anterior chamber depth measurements with Pentacam and Orbscan. *Optom Vis Sci.* 2005;82(9):858–861.
91. Aslani F, Khorrami Nejad M, Aghazadeh Amiri M, Khodaparast M, Asgarizadeh F, Tabatabaei M. Investigation of corneal elevation, astigmatism and best fit sphere in different stages of keratoconus. *J Paramed Sci Rehabil.* 2017;6(2):38–47.
92. Khosravi B, Khorrami-Nejad M, Rajabi S, Amiri M, Hashemian H, Khodaparast M. Characteristics of astigmatism after myring implantation. *Med Hypothesis Discov Innov Ophthalmol.* 2017;6(4):130.
93. Montalbán R, Piñero DP, Javaloy J, Alió JL. Correlation of the corneal toricity between anterior and posterior corneal surfaces in the normal human eye. *Cornea.* 2013;32(6):791–798. doi:10.1097/ICO.0b013e31827bf898
94. Derakhshan R, Mohammad G-B, Ghoreishi SM, Tabatabaee SM, Mohammadi-Nia M. Evaluation of anterior, posterior, and total corneal astigmatism in normal subjects. *Journal of Isfahan Medical School.* 2017;35;1382–1388.
95. Savini G, Versaci F, Vestri G, Ducoli P, Næser K. Influence of posterior corneal astigmatism on total corneal astigmatism in eyes with moderate to high astigmatism. *J Cataract Refract Surg.* 2014;40(10):1645–1653. doi:10.1016/j.jcrs.2014.01.046
96. Hoffmann PC, Hütz WW. Analysis of biometry and prevalence data for corneal astigmatism in 23239 eyes. *J Cataract Refract Surg.* 2010;36(9):1479–1485. doi:10.1016/j.jcrs.2010.02.025
97. Mas D, Espinosa J, Domenech B, Perez J, Kasprzak H, Illueca C. Correlation between the dioptric power, astigmatism and surface shape of the anterior and posterior corneal surfaces. *Ophthalmic Physiol Opt.* 2009;29(3):219–226. doi:10.1111/j.1475-1313.2008.00632.x

98. Piñero DP, Alió JL, Alesón A, Vergara ME, Miranda M. Corneal volume, pachymetry, and correlation of anterior and posterior corneal shape in subclinical and different stages of clinical keratoconus. *J Cataract Refract Surg.* 2010;36(5):814–825. doi:10.1016/j.jcrs.2009.11.012
99. Alpíns N, Ong JK, Stamatelatos G. Corneal topographic astigmatism (CorT) to quantify total corneal astigmatism. *J Refract Surg.* 2015;31(3):182–186. doi:10.3928/1081597X-20150224-02
100. Aslani F, Khorrami-Nejad M, Amiri MA, Hashemian H, Askarizadeh F, Khosravi B. Characteristics of posterior corneal astigmatism in different stages of keratoconus. *J Ophthalmic Vis Res.* 2018;13(1):3. doi:10.4103/jovr.jovr_217_16
101. Eom Y, Kang S-Y, Kim HM, Song JS. The effect of posterior corneal flat meridian and astigmatism amount on the total corneal astigmatism estimated from anterior corneal measurements. *Graefes Arch Clin Exp Ophthalmol.* 2014;252(11):1769–1777. doi:10.1007/s00417-014-2737-9
102. Feizi S, Naderan M, Ownagh V, Sadeghpour F. Distribution of the anterior, posterior, and total corneal astigmatism in healthy eyes. *Int Ophthalmol.* 2018;38(2):481–491.
103. Fitzmaurice GM, Laird NM, Ware JH. *Applied Longitudinal Analysis.* Hoboken, NJ: John Wiley & Sons; 2012.
104. Kim H. Correlation between anterior and posterior corneal astigmatism in total corneal astigmatism. *J Korean Ophthalmic Optics Soc.* 2014;19(3):377–382. doi:10.14479/jkooos.2014.19.3.377
105. Koch DD, Jenkins RB, Weikert MP, Yeu E, Wang L. Correcting astigmatism with toric intraocular lenses: effect of posterior corneal astigmatism. *J Cataract Refract Surg.* 2013;12(39):1803–1809. doi:10.1016/j.jcrs.2013.06.027
106. Srivannaboon S. Internal astigmatism and its correlation to corneal and refractive astigmatism. *J Med Assoc Thai.* 2003;86(2):166–171.
107. Tonn B, Klaproth OK, Kohnen T. Anterior surface-based keratometry compared with Scheimpflug tomography-based total corneal astigmatism. *Invest Ophthalmol Vis Sci.* 2015;56(1):291–298. doi:10.1167/iovs.14-15659
108. Atchison DA, Markwell EL, Kasthurirangan S, Pope JM, Smith G, Swann PG. Age-related changes in optical and biometric characteristics of emmetropic eyes. *J Vis.* 2008;8(4):29. doi:10.1167/8.4.29
109. Lam AK, Douthwaite WA. The ageing effect on the central posterior corneal radius. *Ophthalmic Physiol Opt.* 2000;20(1):63–69. doi:10.1046/j.1475-1313.2000.00469.x
110. Ueno Y, Hiraoka T, Beheregaray S, Miyazaki M, Ito M, Oshika T. Age-related changes in anterior, posterior, and total corneal astigmatism. *J Refract Surg.* 2014;30(3):192–197. doi:10.3928/1081597X-20140218-01
111. Pérez-Escudero A, Dorronsoro C, Sawides L, Remón L, Merayo-Llodes J, Marcos S. Minor influence of myopic laser in situ keratomileusis on the posterior corneal surface. *Invest Ophthalmol Vis Sci.* 2009;50(9):4146–4154. doi:10.1167/iovs.09-3411
112. Sun HJ, Park JW, Kim SW. Stability of the posterior corneal surface after laser surface ablation for myopia. *Cornea.* 2009;28(9):1019–1022. doi:10.1097/ICO.0b013e3181a06f1e
113. Thibos LN, Horner D. Power vector analysis of the optical outcome of refractive surgery. *J Cataract Refract Surg.* 2001;27(1):80–85. doi:10.1016/S0886-3350(00)00797-5
114. Khorrami Nejad M, Ghorbani M, Aghazadeh Amiri M, et al. Refractive outcomes after myring implantation. *J Paramed Sci Rehabil.* 2016;5(4):16–22.
115. Ambrósio R, Klyce SD, Wilson SE. Corneal topographic and pachymetric screening of keratorefractive patients. *J Refract Surg.* 2003;19(1):24–29.
116. Sara ES, Yazdi MR, Mirzajani A, Jafarzadehpur E. Comparison evaluation of belin-ambrosio indices and rabinowitz criteria in refractive surgery candidates. *Rehabil Med.* 2014;3(3):19–25.
117. Ambrósio R, Faria-Correia F, Ramos I, et al. Enhanced screening for ectasia susceptibility among refractive candidates: the role of corneal tomography and biomechanics. *Curr Ophthalmol Rep.* 2013;1(1):28–38. doi:10.1007/s40135-012-0003-z
118. Correia FF, Ramos I, Lopes B, et al. Topometric and tomographic indices for the diagnosis of keratoconus. *Int J Kerat Ect Cor Dis.* 2012;1(2):92–99.
119. Nemeth G, Berta A, Lipecz A, Hassan Z, Szalai E, Modis JL. Evaluation of posterior astigmatism measured with Scheimpflug imaging. *Cornea.* 2014;33(11):1214–1218. doi:10.1097/ICO.000000000000238
120. Ciolino JB, Belin MW. Changes in the posterior cornea after laser in situ keratomileusis and photorefractive keratectomy. *J Cataract Refract Surg.* 2006;32(9):1426–1431. doi:10.1016/j.jcrs.2006.03.037
121. Ciolino JB, Khachikian SS, Cortese MJ, Belin MW. Long-term stability of the posterior cornea after laser in situ keratomileusis. *J Cataract Refract Surg.* 2007;33(8):1366–1370. doi:10.1016/j.jcrs.2007.04.016
122. Hashemi H, Mehravaran S. Corneal changes after laser refractive surgery for myopia: comparison of Orbscan II and Pentacam findings. *J Cataract Refract Surg.* 2007;33(5):841–847. doi:10.1016/j.jcrs.2007.01.019
123. Naroo SA, Charman WN. Changes in posterior corneal curvature after photorefractive keratectomy. *J Cataract Refract Surg.* 2000;26(6):872–878. doi:10.1016/S0886-3350(00)00413-2
124. Nishimura R, Negishi K, Saiki M, et al. No forward shifting of posterior corneal surface in eyes undergoing LASIK. *Ophthalmology.* 2001;6(114):104–107.
125. Vicente D, Clinch TE, Kang PC. Changes in posterior corneal elevation after laser in situ keratomileusis enhancement. *J Cataract Refract Surg.* 2008;34(5):785–788. doi:10.1016/j.jcrs.2007.12.040
126. Koch DD, Lindstrom RL, editors. Controlling Astigmatism in Cataract Surgery. *Seminars in Ophthalmology.* England: Taylor & Francis; 1992.
127. Ferrer-Blasco T, Montés-Micó R, Peixoto-de-Matos SC, González-Méjome JM, Cerviño A. Prevalence of corneal astigmatism before cataract surgery. *J Cataract Refract Surg.* 2009;35(1):70–75. doi:10.1016/j.jcrs.2008.09.027
128. Hoffer KJ. Biometry of 7,500 cataractous eyes. *Am J Ophthalmol.* 1980;90(3):360–368. doi:10.1016/s0002-9394(14)74917-7
129. Akura J, Kaneda S, Hatta S, Matsuura K. Controlling astigmatism in cataract surgery requiring relatively large self-sealing incisions. *J Cataract Refract Surg.* 2000;26(11):1650–1659. doi:10.1016/S0886-3350(00)00484-3
130. Müller-Jensen K, Fischer P, Siepe U. Limbal relaxing incisions to correct astigmatism in clear corneal cataract surgery. *J Refract Surg.* 1999;15(5):586–589.
131. Lever J, Dahan E. Opposite clear corneal incisions to correct pre-existing astigmatism in cataract surgery. *J Cataract Refract Surg.* 2000;26(6):803–805. doi:10.1016/S0886-3350(00)00378-3
132. Reitblat O, Levy A, Kleinmann G, Abulafia A, Assia EI. Effect of posterior corneal astigmatism on power calculation and alignment of toric intraocular lenses: comparison of methodologies. *J Cataract Refract Surg.* 2016;42(2):217–225. doi:10.1016/j.jcrs.2015.11.036
133. Till JS, Yoder PR Jr, Wilcox TK, Spielman JL. Toric intraocular lens implantation: 100 consecutive cases. *J Cataract Refract Surg.* 2002;28(2):295–301. doi:10.1016/S0886-3350(01)01035-5
134. Yang C-N, Shen EP, Hu F-R. Laser in situ keratomileusis for the correction of myopia and myopic astigmatism. *J Cataract Refract Surg.* 2001;27(12):1952–1960. doi:10.1016/S0886-3350(01)01071-9
135. Mendicute J, Irigoyen C, Aramberri J, Ondarra A, Montes-Mico R. Foldable toric intraocular lens for astigmatism correction in cataract patients. *J Cataract Refract Surg.* 2008;34(4):601–607.

136. Matsumoto Y, Hara T, Chiba K, Chikuda M. Optimal incision sites to obtain an astigmatism-free cornea after cataract surgery with a 3.2 mm sutureless incision. *J Cataract Refract Surg.* 2001;27(10):1615–1619. doi:10.1016/S0886-3350(01)00876-8
137. Maloney WF, Sanders DR, Pearcy DE. Astigmatic keratotomy to correct preexisting astigmatism in cataract patients. *J Cataract Refract Surg.* 1990;16(3):297–304. doi:10.1016/S0886-3350(13)80698-0
138. Lindstrom RL, Lindquist TD. Surgical correction of postoperative astigmatism. *Cornea.* 1988;7(2):138–148.
139. Nichamin LD. Astigmatism control. *Ophthalmol Clin North Am.* 2006;19(4):485–493. doi:10.1016/j.ohc.2006.07.004
140. Gills JP. Cataract surgery with a single relaxing incision at the steep meridian. *J Cataract Refract Surg.* 1994;20(3):368–369.
141. Sun X-Y, Vicary D, Montgomery P, Griffiths M. Toric intraocular lenses for correcting astigmatism in 130 eyes. *Ophthalmology.* 2000;107(9):177.6–81. doi:10.1016/S0161-6420(00)00266-9
142. Stojanovic A, Nitter T. Excimer laser in the treatment of myopic astigmatism; outcomes of laser in situ keratomileusis and photorefractive keratectomy. *J Cataract Refract Surg.* 2001;27:1263–1277.
143. Tadras A, Habib M, Tejwani D, Von Lany H, Thomas P. Opposite clear corneal incision to correct preexisting astigmatism in cataract surgery. *J Cataract Refract Surg.* 2004;30(2):414–417. doi:10.1016/S0886-3350(03)00649-7
144. Khokhar S, Lohiya P, Murugesan V, Panda A. Corneal astigmatism correction with opposite clear corneal incisions or single clear corneal incision: comparative analysis. *J Cataract Refract Surg.* 2006;32(9):1432–1437. doi:10.1016/j.jcrs.2006.04.010
145. Gills JP, Van Der Karr M, Cherchio M. Combined toric intraocular lens implantation and relaxing incisions to reduce high preexisting astigmatism. *J Cataract Refract Surg.* 2002;28(9):1585–1588. doi:10.1016/S0886-3350(01)01315-3
146. Bazazi N, Barazandeh B, Mani K, Rasouli M. Opposite clear corneal incisions versus on-axis incision during phacoemulsification to correct pre-existing astigmatism. *Bina J Ophthalmol.* 2008;13(3):305–308.
147. Feizi S, Zare JM, Montahaei T. Current approaches for management of postpenetrating keratoplasty astigmatism. *Bina J Ophthalmol.* 2012;17:162–170.
148. Javadi MA, Feizi S, Mirbabaie F, Mohammadi P, Rastegarpour A. Graft refractive surgery for post-DALK atigmatism in keratoconus. *Bina J Ophthalmol.* 2009;14(4):361–366.
149. Joshaghani M, Jamshidi AM, Foroutan AR, Meshkot MR. Limbal relaxing incision to correct pre-existing corneal astigmatism in patients undergoing phacoemulsification. *Bina J Ophthalmol.* 2007;13(1):32–36.
150. Lee H, Kim EK. Corneal astigmatism analysis for toric intraocular lens implantation: precise measurements for perfect correction. *Curr Opin Ophthalmol.* 2015;26(1):34–38. doi:10.1097/ICU.000000000000119

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