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Etiology and Clinical Presentation of Astigmatism

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1. Introduction

Astigmatism exists to some extent in virtually every eye. Multiple terms include the word "astigmatism": regular astigmatism, fully correctable by a cylinder; irregular astigmatism (with dual use: both as the refractive error not correctable by sphere and cylinder, and as a component in Fourier analysis); and components in Zernike's polynomials (primary and secondary astigmatism).
The optical apparatus is created by an interaction of the cornea, the crystalline lens and the fovea. Any imperfection translates into a refractive error. The sphere component of the refractive error is influenced by the relationship between all three components. Any other refractive error, including any astigmatism, is influenced by the cornea and crystalline lens only. The aetiology of astigmatism is highly diverse. Its aetiology and its presentation are outlined in this chapter

2. Types of astigmatism

To many, the term astigmatism is replaceable with cylinder. This certainly is not the case. Astigmatism is usually described as regular and as irregular astigmatism.

2.1 Regular astigmatism

Regular astigmatism is the type or refractive error correctable by a cylinder lens. Such a lens can be used in spectacles, in a soft contact lens, and in an intraocular lens – replacing the crystalline lens or being added to it.
A perfect spherocylindrical apparatus is composed solely of spheres and cylinders. A positive sphere is a lens that converges parallel light rays to a single spot. The amount of conergence of the light is inversely proportional to the distance from the source. If the distance is expressed in meters, the vergence is in units of dioptres.

$$\text{Diopters} = 1/\text{Distance in meters} \tag{1}$$

Thus, a +5 diopter sphere lens converges parallel light rays to a single spot, 1/5 of a meter, or 20 cm, away from it.
A positive cylinder is a lens that converges parallel light rays to a straight line, parallel to the cylinder axis. Here again, the amount of convergence of the light is inversely proportional to

the distance from the source. A +5 diopter cylinder lens converges parallel light rays to a straight line, as long as the length of the lens and parallel to its axis, 20 cm away from it.
In regular astigmatism, the optical power of the optical system can be perfectly described by a single sphere and a single cylinder. The actual combined lens is neither a sphere nor a cylinder. A convex (positive, convergent) pure sphere lens is part of a perfect sphere. The radius of curvature of the lens is identical in all meridians. A convex spherocylindrical lens is like a "bent" sphere. It may look more like a part of an american football, or a part of a donut: the radius of curvature in two perpendicular meridians is not the same.
While the sphere power of the optical system of the human eye is usually more than 60 diopters, the cylinder is much lower. Typically, the cylindrical power of an eye that has not undergone surgery is less than one diopter, seldom surpassing 2 or 3 diopters.
A refractive error caused by a cylinder is corrected with a negative cylinder placed on the same axis. When the correct lenses are placed in the correct orientation, the eventual image is sharp.

2.1.1 With-the-rule and against-the-rule astigmatism

The condition in which the meridian of greatest power is vertical, or within 30 degrees of the vertical, is most common and it is called with-the-rule astigmatism. It is corrected with a plus cylinder at the same vertical axis, or with a minus cylinder at an axis perpendicular to it. When the meridian of greatest power is horizontal, or within 30 degrees of the horizontal, it is called against-the-rule astigmatism. When the astigmatism is neither with the rule nor against the rule it is called oblique astigmatism.

2.2 Irregular astigmatism

In the traditional representation of refractive errors, any refractive error not corrected by a sphere or a cylinder is an irregular astigmatism. While regular astigmatism, or a spherocylindrical refractive error, is a theoretical approximation, irregular astigmatism is what happens in real life. Any irregularity in the surfaces of the cornea and the crystalline lens and any local change in the refractive index of the lens or the cornea changes the optical power of the system in that location in a way that a spheroclylindrical lens can not fully correct.

2.3 Presentation by Zernike polynomials

The refractive error of the eye can be presented in several methods. The measurement of optical aberrations is based on the principle of Tscherning's aberroscope (Mierdel et al., 1999), Hartmann-Shack's aberroscope (Moreno-Barriuso et al., 2001) or light ray tracing (Moreno-Barriuso et al., 2001). The joint representation of all the raw aberroscope data constitutes the spot diagram, which can be taken as a rough estimate of the shape of the retinal point spread.
The results of the measurement are often presented by the Zernike polynomials. These polynomials were invented by Frits Zernike, (1888-1966), a Dutch Nobel prize in physics laureate, as a research tool in optics. The Zernike polynomials are used in ophthalmology to describe and display the optical aberrations of the entire optical pathway or of any of its components.
Figure 1 presents all the optical aberrations and Zernike polynomial values (Zernike's coefficients) of the anterior corneal surface (corneal topography, Wavelight, Allegro Topolyzer) of a normal eye, computed to the 8^{th} order.

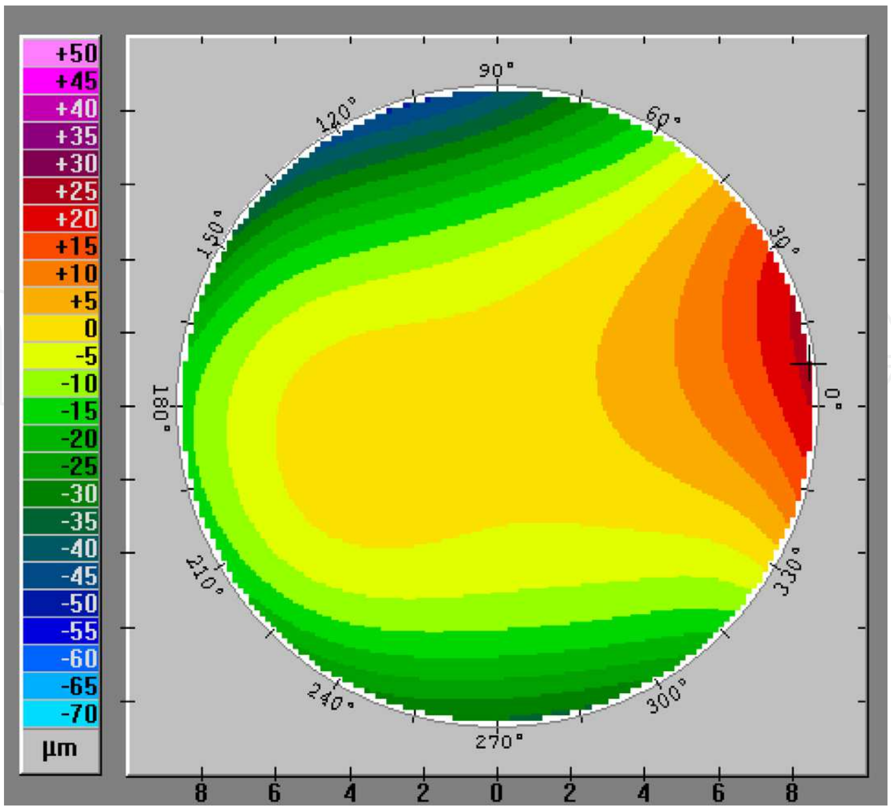

Fig. 1. Zernike analysis of a normal corneal topography

The first orders of the Zernike polynomials, Z_0^0 (named piston) and Z_1^1, Z_1^{-1} (named tilt), have little direct meaning on refraction. The second orders of the Zernike polynomials are Z_2^0, (sphere, Figure 2) and Z_2^2, Z_2^{-2}, (cylinder, Figure 3, Figure 4). In traditional nomenclature, these would the sphere and cylinder of the refractive error. These can be corrected with spherocylindrical spectacle lenses, soft contact lenses or intraocular lenses.
Figure 5 represents the sum of all the optical aberrations of the higher orders (in the specific example, 3rd to 8th orders were calculated). These are named high order aberrations, or HOA's. HOA's can not be corrected with spherocylindrical spectacle lenses, soft contact lenses or intraocular lenses. Correction of HOA's can be attempted in several methods: Using rigid contact lenses to minimize the HOA's originating from the anterior corneal surface; using excimer laser to reshape the anterior corneal surface so that all optical aberrations are treated (wavefront guided ablation); using excimer laser to reshape the anterior corneal surface so that aberrations originating from the anterior corneal surface are treated (topography guided ablation); using an intraocular lens that, apart from correcting sphere and sometimes cylinder, can also address other aberrations, namely spherical aberrations (Z_4^0).

2.4 Presentation by Fourier analysis

Fourier analysis is another way of representing the refractive qualities of a system (e.g. a whole eye) or of an optical component within the system (e.g. the anterior corneal surface). Fourier analysis is named after Jean Baptiste Joseph Fourier (1768-1830), a French mathematician and physicist, who showed that representing a function by a trigonometric series can greatly simplify its study. Fourier series harmonic analysis can be applied to

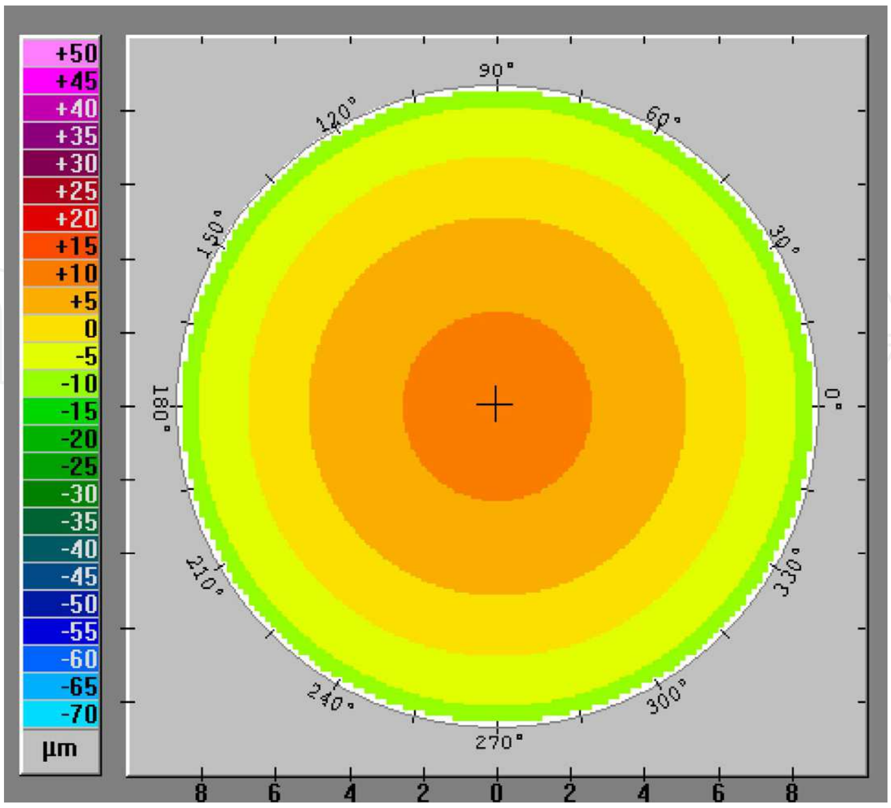

Fig. 2. Isolated Zernike coefficient Z_2^0 (sphere) of a normal corneal topography

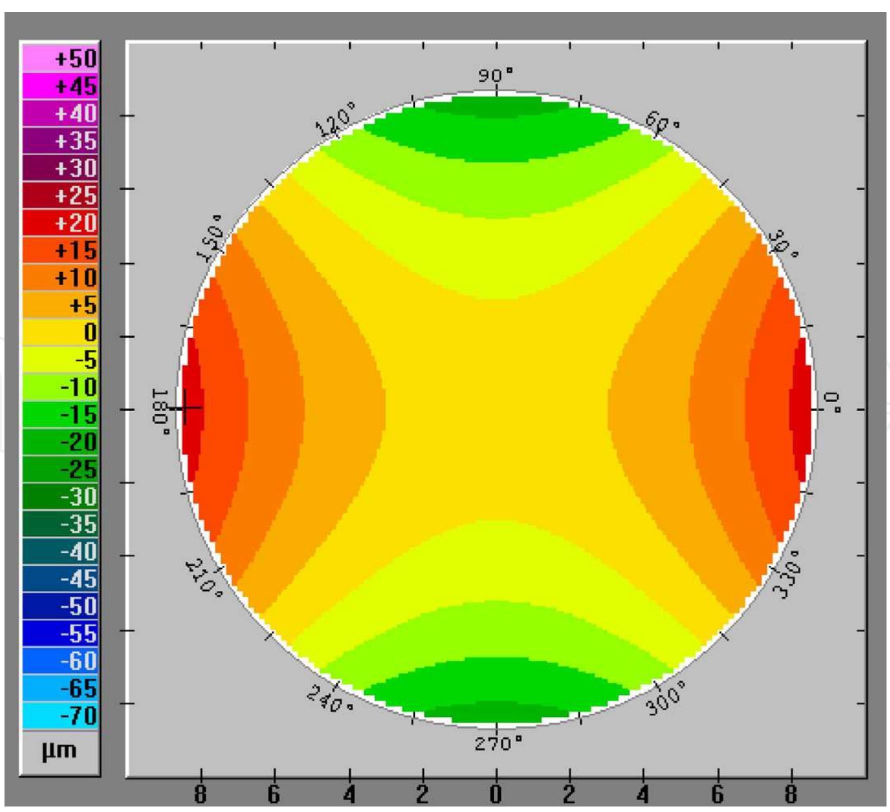

Fig. 3. Isolated Zernike coefficient Z_2^2 (cylinder) of a normal corneal topography

topographic analysis (Maeda, 2002). A Fourier series consists of trigonometric sine and cosine functions with increasing coefficients. A Fourier series can be used to transform any periodical functions into trigonometric components. Therefore, by applying the Fourier analysis to the polar data of the dioptric corneal power for each mire, one can break down the complex information given in corneal topography into spherical, regular astigmatism, decentration, and irregular astigmatism components. Figure 6 presents the Fourier analysis of the anterior corneal surface (corneal topography, Wavelight, Allegro Topolyzer) of the same normal eye in as in figures 1-5. Irregular astigmatism (termed "Irregularities") is of a much lower amplitude than regular astigmatism in this normal cornea.
It seems that for the presentation of the optical system of the eye, Zernike polynomials are better suited than Fourier analysis (Yoon et al., 2008). The Zernike method outperformed the Fourier method when representing simulated wavefront data from topography maps. Even 2nd through 5th order Zernike polynomials were enough to outperform the Fourier method in all populations. Up to 9th order Zernike modes may be required to describe accurately simulated wavefront in some abnormal eyes.

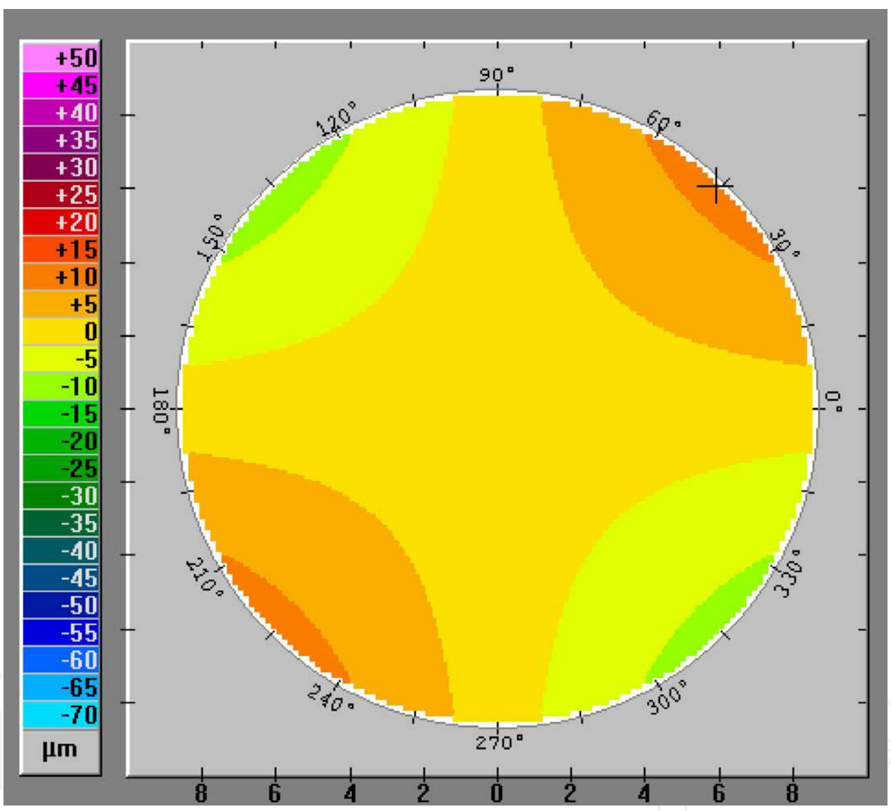

Fig. 4. Isolated Zernike coefficient Z_2^{-2} (cylinder) of a normal corneal topography

3. Prevalence of astigmatism

It appears that the prevalence of astigmatism in mainly population related. Age probably plays a smaller role.

3.1 Populations

Corneal astigmatism and total refractive astigmatism were measured in a presbyopic population in Germany (Hoffmann & Hutz, 2010). Mean corneal astigmatism was 0.98±0.78

diopters. Less than 1.00 D of corneal and refractive astigmatism was found in 63.96% and 67.97% respectively. Astigmatism value ≥1.00 D and <2.00 D in 27.95% and 22.55% respectively, ≥2.00 D and <3.00 D in 5.44% and 6.09% respectively, ≥3.00 D and < 4.00 D in 1.66% and 2.18% respectively, ≥4.00 D and <5.00 D in 0.56% and 0.80% respectively, ≥5.00 D and <6.00 D in 0.25% and 0.28% respectively and only 0.18% and 0.13% respectively had astigmatism of 6.00 D or more. Lekhanont et al., 2011, reported on corneal astigmatism in cataract candidates in Bangkok, Thailand. Less than 0.50 D was found in 19.71%, ≥0.50 D and <1.00 D in 42.49%, ≥1.00 D and <2.00 D in 29.92%, ≥2.00 D and <3.00 D in 6.30% and 3.00 D and above in 1.58%. KhabazKhoob et al. (2010) found the corneal astigmatism in residents of Tehran, Iran to be 0.98 D (C.I. 0.89-1.06), with no apparent age effect.

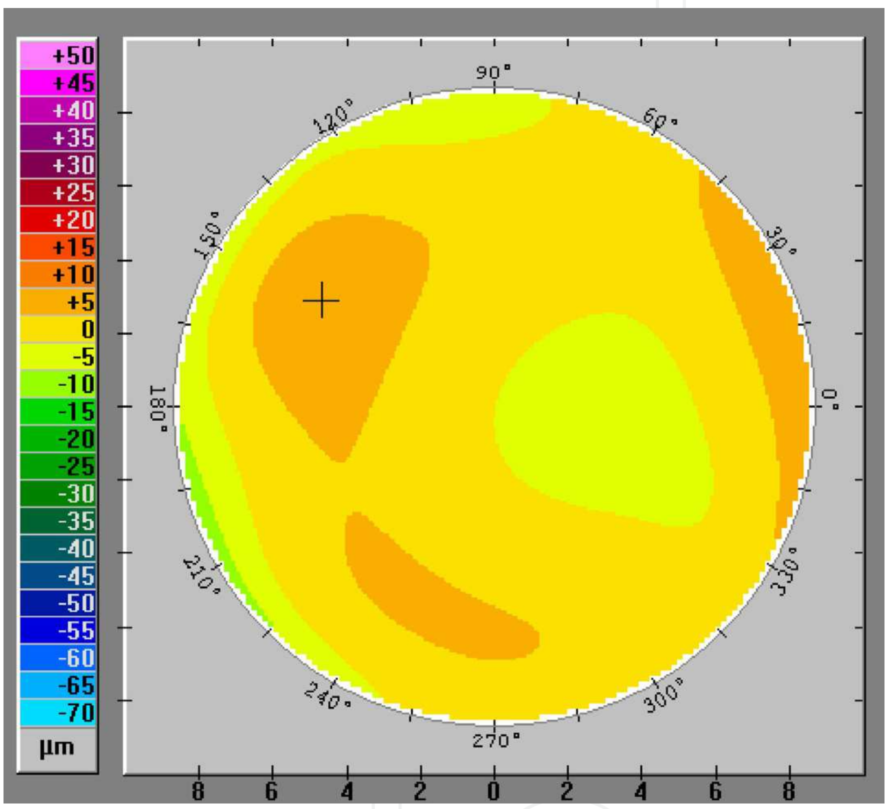

Fig. 5. Combined Zernike coefficient Z_2 to Z_8 (high order aberrations) of a normal corneal topography

Astigmatism was studied (Allison, 2010) in a Polish immigrant population in Chicago. Fifteen percent of the patients exhibited astigmatism ≥1.00 D.

Prevalence of astigmatism >1.00 D in indigenous Australians within central Australia (Landers et al., 2010) was found to be 6.2%.

Direct comparison between these different population groups is not easy, because of different cutoff points and different age groups. The impression from the above figures is that there seems to be a substantial population or location difference in prevalence and magnitude of astigmatism between these studies.

3.2 Children

The astigmatism in young children (6-72 month old) was studies in African American and Hispanic children (Fozailoff et al. 2011). Mean refractive astigmatism was 0.58±0.61 D

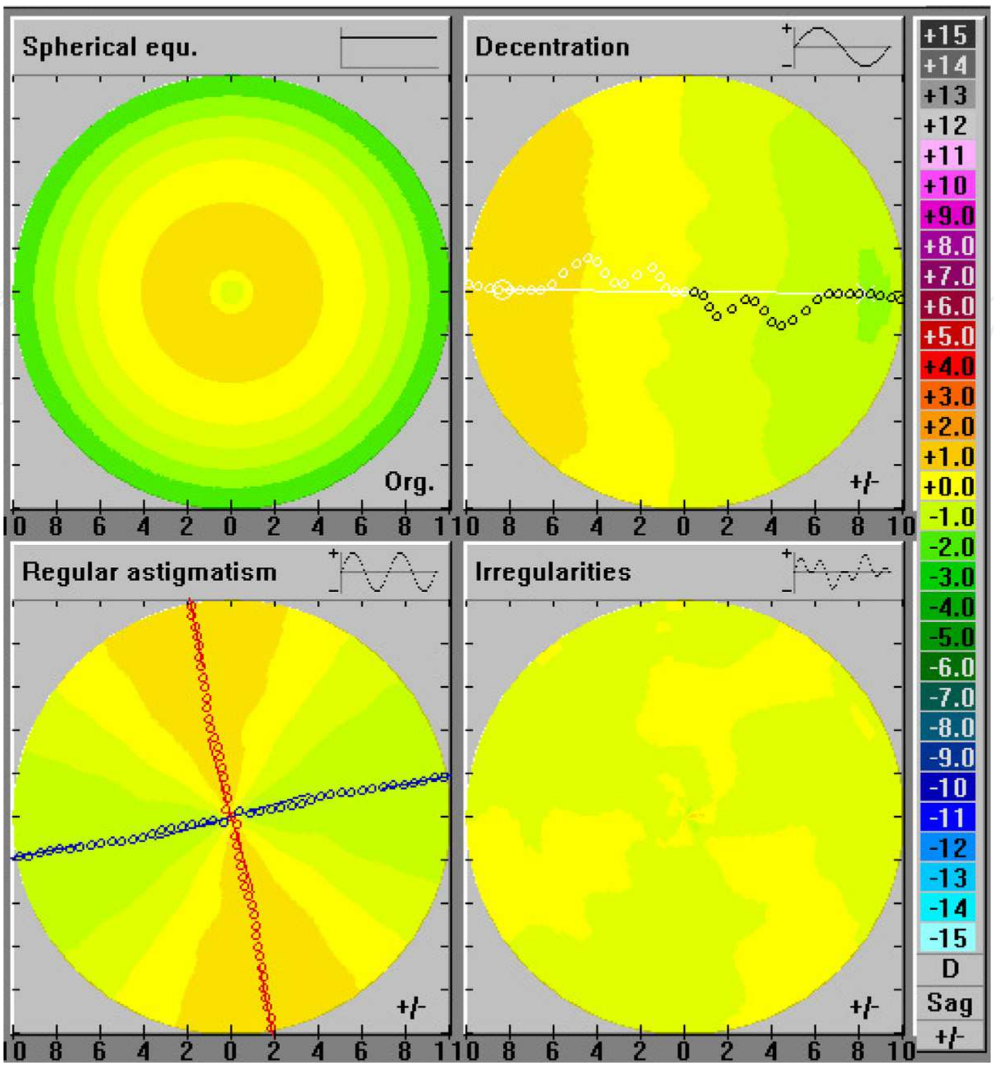

Fig. 6. Fourier analysis of a normal corneal topography

(mean±SD) in the right eye, 0.58±0.60 D in the left eyes in the African American population, and 0,66±0.76 D in the right eye, 0.64±0.75 D in the left eye in the Hispanic population. The overall prevalence of astigmatism ≥1.50 D was 12.7% in African Americans and 16.8% in Hispanic children. Prevalence of astigmatism ≥1.50 D decreased with age group in both ethnicities (P<0.0001). The overall prevalence of astigmatism ≥3.00 D was 3.0% for Hispanic and 1.2% for African American children. Astigmatism ≥3.00 D showed no significant trend with age in either ethnicity (P≥0.50).

A population based (Stratified random clustering) method was used to examine refractive and corneal astigmatism in white school children in Northern Ireland (O'Donoghue, 2011). The prevalence of refractive astigmatism (≥1.00D) did not differ significantly between 6-7-year-old children (24%, 95% CI 19-30) and 12-13-year-old children (20%, 95% CI 14-25). The prevalence of corneal astigmatism (≥1D) also did not differ significantly between 6-7-year-old children (29%, 95% CI 24-34) and 12-13-year-old children (25%, 95% CI 21-28). Whilst levels of refractive astigmatism and corneal astigmatism were similar, refractive astigmatism was predominantly oblique (76%, 95% CI 67-85 of 6-7-year-olds; 59% 95% CI 48-70 of 12-13-year-olds), but corneal astigmatism was predominantly with-the-rule (80%, 95% CI 72-87 of 6-7-year-olds; 82% 95% CI 74-90 of 12-13-year-olds).

Prevalence of refractive astigmatism was studied in preschool children in Taiwan (Lai et al. 2010). In this group, 49.5% of the total had astigmatism ≥0.50 D, 25.4% had 0.75 D or more, and 13.3% had 1.00 D or more. The prevalence of astigmatism >1.50 D was 4.0% (95% CI, 2.8%-5.2%). The prevalence of astigmatism was unassociated with age or sex. Children with with-the-rule astigmatism had greater mean cylinder power than those with against-the-rule or oblique astigmatism. Refractive astigmatism correlated with its corneal component.
The age effect is not clear in these studies. Age did and did not play a role in the magnitude of astigmatism in different studies. This may be a result of the population differences, as seen in the previous paragraphs.

4. Location of astigmatism

As stated above, astigmatism can originate from any refractive surface in the optical system. Each surface adds some astigmatism, regular and irregular, and the total astigmatism of the system is the product of all components. In some cases, the effect of one surface may negate the effect of another, thus improving the total result. This fact is utilized in refractive surgery, when changes of the anterior corneal surface are made in an attempt to lower the total optic aberrations of the entire eye, including sphere, cylinder and high order aberrations.

4.1 Cornea

The corneal surface (and mainly the anterior corneal surface) is probably the largest source of astigmatism in the eye. It is not the only source. A study in school children (O'Donoghue, 2011) found that levels of refractive astigmatism and corneal astigmatism were similar, but refractive astigmatism was predominantly oblique (76% of 6-7-year-olds; 59% of 12-13-year-olds), while corneal astigmatism was predominantly with-the-rule (80% of 6-7-year-olds; 82% of 12-13-year-olds). Another cylindrical vector being added to the corneal cylinder vector, causing a new direction of the compound vector explains this finding.

4.1.1 Anterior corneal surface

In most measurement devices, the data on the corneal power including corneal astigmatism is derived from the anterior corneal surface, by use of reflection rather than refraction to compute curvature, and then to assess refraction by assuming the refractive index of the cornea, and the posterior corneal curvature. This assumption is close to reality in most normal eyes, but grossly incorrect in others. A large exception is the cornea after excimer laser refractive surgery, when the shape of the anterior corneal surface is markedly changed, while the posterior corneal surface is roughly unchanged.
Measuring the anterior corneal surface only, several studies have reported age-related changes to corneal astigmatism. A shift in the axis of corneal astigmatism from with the rule toward against the rule associated with increasing age was found.
Gudmundsdottir et al. (2000) did autokeratometry on adults in Reykjavik. Using linear regression the change to against the rule was 0.14 D (0.14 D in males and 0.13 D in females) in five years. The Distribution of corneal astigmatism 0.75 D or more measured by keratometry shows a marked shift towards against-the-rule astigmatism. Their younger age groups (50-59 year old) had ~5% against-the-rule astigmatism and 60%-70% with-the-rule astigmatism. The older age groups change gradually, and the 80+ year olds have ~5% with-

the-rule astigmatism and ~60% against-the-rule astigmatism. Oblique astigmatism prevalence retained 25% to 35% levels in all age groups, 50 years and above.

Gudmundsdottir et al. (2005) found in a follow-up study an against-the-rule astigmatic shift in keratometry in adults in Reykjavik. The shift, for a 5 year period, was 0.03 D in people 50-59 year old, 0.08 D in 60-69 year olds, and 0.17 on 70 or more year olds.

Goto et al. (2001) found that although corneal curvature in younger men and women was similar, people older than 50 had gender related differences. In older men, 81.1% had against-the-rule astigmatism and 18.9% had with-the-rule or no astigmatism. In contrast, in older women, 22.5% had against-the-rule astigmatism and 77.5% had with-the-rule or no astigmatism. The differences between genders in terms of the frequency of against-the-rule astigmatism were statistically significant ($p < 0.001$). With age, the pattern of astigmatism tends to change from with-the-rule to against-the-rule. Older men had a significantly higher potential for this change than women ($p < 0.001$).

Asano et al. (2005) examined the astigmatism in middle-aged and elderly Japanese. Corneal astigmatism (mean±SD) slightly increased over time: 0.83±0.57, 0.82±0.61, 0.85±0.63, 0.95±0.70 and 0.86±0.63 D in the 40–49 year old, 50–59 year old, 60–69 year old, 70–79 year old and all groups respectively. The axis gradually changed over time, from with-the-rule astigmatism to against-the-rule astigmatism. With-the- rule astigmatism was the most frequent in the 40s age group; its prevalence was over 60% in this group and decreased with age to ~25%. In contrast, the prevalence of against-the- rule astigmatism increased with age from ~15% to ~50% ($P<0.0001$)

4.1.2 Posterior corneal surface

In contrast to the abundance of research on the anterior corneal surface, much less was studied concerning the posterior corneal surface. However, instruments capable of capturing the posterior corneal curvature made such research possible.

In a report from Taipei, Taiwan, (Ho et al. 2009), a rotating Scheimpflug camera (Pentacam) was used. Subjects with healthy corneas were randomly selected from the Taipei City Hospital ophthalmology clinic visitors. Astigmatisms of the anterior and posterior corneal surfaces were determined. The total corneal astigmatism was derived using power vector summation and vergence tracing. Age-related changes to corneal astigmatism were evaluated using polar value analysis.

For the anterior and total cornea, the proportion of with-the- rule astigmatisms decreased and those of oblique and against-the-rule astigmatisms increased with age. For the posterior cornea, most eyes displayed against-the-rule astigmatisms in all age groups. There was a significant trend toward against-the-rule astigmatism associated with increasing age for both anterior and total corneal astigmatisms (mean changes of -0.18 and -0.16 diopters/5 years, respectively), and toward with the rule in posterior corneal astigmatism (a mean change of 0.022 diopters/5 years). Regarding shape changes, a ''flat meridian toward a more vertical orientation'' trend with increasing age for both the anterior and posterior corneal surfaces was observed (mean changes of 0.0295 and 0.0224 mm/5 years, respectively). In the posterior cornea, proportions of with-the-rule, oblique, and against-the-rule astigmatisms are 0%, 1.7%, and 98.3% in the 21–30 age group and 9.1%, 2.3%, and 88.6% in the ≥71 age group. In contrast, in the anterior cornea, the proportions of with-the-rule, oblique, and against-the-rule astigmatisms are 91.4%, 5.2%, and 3.4% in the 21–30 age group and 31.8%, 29.5%, and 38.6% in the ≥71 age group. The posterior corneal surface compensated for the astigmatism arising from the anterior corneal surface in 91.4% and 47.7% of eyes in the 21–30 and ≥71 year groups, respectively.

Using similar equipment, Mas et al. (2009) compared the optics of the anterior and posterior corneal surfaces. Their data shows that there was a low correlation between the astigmatic components of both surfaces: for the power vectors J_0 of the first and second corneal surfaces, the regression line is: $y = -0.13x + 0.17$; $r^2 = 0.49$; $p < 0.01$. For the power vectors J_1 of the first and second corneal surfaces, the regression line is $y = -0.10x -0.00$; $r^2 = 0.23$; $p < 0.01$.

4.2 Crystalline lens

Shankar & Bobier (2004) examined preschool children (mean age ±SD 51.1±8.4 months). They calculated the lenticular astigmatism by substracting corneal astigmatism from the total refractive astigmatism. This method ignores the effect of the posterior corneal surface. However, the results of this paper are that the magnitude of total and corneal cylinder was significantly greater in high astigmats, but overall lenticular cylinder was similar in both groups. However, the Fourier transforms showed high astigmats to have significantly lower lenticular J_0 (with-the-rule or against-the-rule astigmatism) and higher lenticular J_{45} (oblique astigmatism) than the normal astigmats. Both the high and the low astigmatism groups in the study had higer corneal astigmatism than total astigmatism, so that the lenticular component (and actually, the posterior corneal component as well) of the astigmatism served to lower the astigmatic effect of the anterior corneal surface.

4.2.1 Structural causes

Physical changes influencing the crystalline lens can also cause change in the optical properties an doptical effect of the lens.

A 6-year-old boy developed lenticular astigmatism with a regular component of 5.5 D within 6 weeks of a penetrating scleral injury that included vitreous prolapse (Ludwig et al. 2002). Visible indentational folds in the posterior lens capsule, caused by anterior vitreous fibers and anterior hyaloid, were presumed to be the origin of the astigmatism. A pars plana vitrectomy partially helped, reducing the preoperative astigmatism to 4.0 D.

Another paper (Urrets-Zavalia, 1989) described lenticular astigmatism following subluxation of the crystalline lens.

4.2.2 Cataract

The connection of cataract formation and appearance of lenticular astigmatism has been reported many years ago (Vaughn & Schepens, 1981). Rapidly progressive lenticular astigmatism related to cataract formation caused a cylinder of 12.00 D (Tint et al. 2007), and another case was reported (Tatham & Prydal, 2008), where the astigmatism changed from 0.25 to 5.00 during a period of 20 months without signs of lens opacity, returning to 0.25 D apter cataract surgery. As with myopic shift, changes in the aging lens can cause astigmatism.

5. Etiology

Astigmatism may arise from many reasons. The following sections are an effort to sample the vast literature dealing with etiology of astigmatism.

5.1 Corneal thinning disorders

Several noninflammatory conditions may lead to corneal thinning, including keratoconus, pellucid marginal degeneration, keratoglobus and Terrien's marginal degeneration. Other corneal thinning disorders are secondary to or associated with inflammation and necrosis, such as peripheral ulcerative keratitis and Mooren ulcer (Jain et al. 2011). To this list one must add laser in situ keratomileusis (LASIK) as an iatrogenic cause of a keratoectatic disorder. All these disorders are associated with regular and irregular astigmatism, ranging from low magnitude to many diopters.

5.2 Post corneal surgery

The cornea is a physical structure under internal pressure. Surgical intervention in the physical integrity of the cornea, intended or unintended, is a possible cause of change of shape and optical properties. The cornea is subject to many forms of surgery, and induced astigmatism evolves in many of the patients.

5.2.1 Penetrating keratoplasty

Penetrationg keratoplasty is the ocular procedure with the largest wound length, and the donor tissue is held in place with multiple sutures. Astigmatism is the common result in most cases. A review (Price MO & Price FW, 2010) reports of average astigmatism of 4.2, 4.7 and 3.9 D, 2, 2 and 8 years after surgery respectively, in three articles on 297 patients. Much of the astigmatism is irregular, forcing patients to resort to rigid gas permeable contact lenses rather than spectacles or soft contact lenses.

5.2.2 Posterior lamellar keratoplasty

A review (Price MO & Price FW, 2010) reports of a low average refractive cylinder of 1.2, 1.5 and 1.5 D achieved 6, 6 and 3 months following Descemet stripping automated endothelial keratoplasty (DSAEK). Similar results were reported following Descemet membrane endothelial keratoplasty (DMEK): 0.85 D, close to the average astigmatism of a normal cornea.

5.2.3 Anterior lamellar keratoplasty

Astigmatism following deep anterior lamellar keratoplasty (DALK) was reported in two groups (Kubaloglu et al. 2011): descemetic DALK (dDALK), or pre-descemetic DALK (pdDALK). The results were similar: 3.73±1.42 on the pdDALK group (mean±SD), and 3.52±1.53 in the dDALK group.

In a small group of patients, femtosecond laser-assisted sutureless anterior lamellar keratoplasty (FALK) was shown in 13 patients not to induce significant astigmatism (Shousha et al 2011). Preoperatine cylinder was 1.8±2.2 D (mean±SD), while 12 month cylinder measured in all patients was 2.2±2.3 D. However, adjunctive surgeries included phototherapeutic keratectomy, a procedure that may have improved surgically induced astigmatism.

5.2.4 Refractive surgery

Refractive surgery is basically aimed at reducing refractive errors, including astigmatism. Astigmatism is induced only when complications occur during or after surgery.

5.2.4.1 Excimer laser

Several complications of LASIK such as central islands, corneal ectasia and decentration can induce regular and irregular astigmatism (Johnson and Azar, 2001).

Eyes that had decentered LASIK ablation were compared to eyes that underwent uneventful surgery (Padmanabhan et al. 2009). There was a statistically significant ($P<.05$) linear correlation between the distance of decentration and the magnitude of induced tilt, coma and secondary astigmatism. The induced changes in tilt, oblique astigmatism, vertical coma, and spherical aberration were statistically significantly higher in eyes with decentered ablations than in eyes with well-centered ablations. A statistically significantly higher percentage of eyes (87%) with well-centered ablations than eyes with decentered ablations (70%) had a postoperative uncorrected visual acuity (UCVA) of 20/20 or better.

Proper placement of the treatment is crucial, and eye tracking devices are used to ensure that. In a study on the effect of different eye tracking methods during LASIK, some 400 eyes were operated in three groups (Prakash et al 2011). In the first group, no iris registration was used (no-iris-registration group). In a second group, preablation static iris registration was performed (static-iris-registration group). In the third group, preablation iris registration with dynamic rotational eye tracking was used (dynamic-iris-registration group). Alpins analysis showed that the indices for assessment of astigmatism outcomes were best in the dynamic-iris-registration group followed by the static-iris-registration group: better ability to treat in the right place yielded better ability to predict the outcome.

5.2.4.2 Incisional

Several incisional procedures are aimed to induce a cylinder effect, therefore undercorrection or over correction can be an expected result. Other procedures are aimed at correcting sphere (radial keratotomy, hexagonal keratotomy) and not affecting cylinder, but less than perfect construction of the incisions can still have an asymmetric effect.

Radial keratotomy erduced myopia by inducing instability to the peripheral cornea. The effect can be unpredictable. In the report of the PERK (prospective evaluation of radial keratotomy) study (Waring et al 1985), ten percent of patients increased astigmatism by more than 1.00 diopter. In a large scale survey of radial keratotomy complications (Marmer, 1987), irregular astigmatism was one of the reported complications.

Hexagonal keratotomy was used to treat hypermetropia. One article reports of 18 consecutive eyes of 12 patients that underwent hexagonal keratotomy (Werblin 1996). In addition to the primary procedures, 14 enhancements were required in seven eyes for both astigmatism and undercorrection. The author declared he no longer performed or recommended hexagonal keratotomy.

5.3 Post cataract surgery

Cataract surgery is often referred to as a refractive procedure. Cataract surgery is among the safest surgical procedures, but as the most performed ophthalmic procedure, every pro mil of complication is translated to thousands of suffering patients.

5.3.1 Wound related

Large incision cataract surgery was compared with phacoemulcification (Minassian et al 2001). The two planned treatments were: extracapsular cataract extraction (ECCE), and small incision surgery by phacoemulsification. In ECCE, a 12–14 mm corneoscleral section was made, while in phacoemulcification a self sealing 3.2 mm clear corneal incision was made on the steep axis of the corneal astigmatism. The post operative astigmatism ws markedly different in both groups. The phacoemulcification group kept the astigmatism just under 1 D, similar to the preoperative value. The ECCE group' on the other end, had a rise

of astigmatism to more than 3 D, 3 weeks after surgery, declining and stabilizing 6 and 12 months after surgery at slightly less than 1.5 D.
Manual small-incision cataract surgery (SICS) was compared with phacoemulcification (Venkatesh et al 2010). SICS was performed through a 6.5 to 7.0 mm superior frown-shaped sclerocorneal tunnel, while phacoemulsification was performed through a temporal 3.0 mm scleral tunnel incision The mean surgically induced astigmatism (SIA) was 0.80±0.24 D in the phacoemulsification group and 1.20±0.36 D in the manual SICS group.
Smaller incison were compared in a prospective randomized study (Can et al 2010). Patients had standard coaxial (2.8 mm incisions), microcoaxial (2.2 mm incisions), or biaxial microincision (1.2 to 1.4 mm trapezoidal incisions) phacoemulsification. The mean SIA 90 days postoperatively was 0.46 diopter (D), 0.24 D, and 0.13 D, respectively (P<.01). Biaxial microincision surgery, with the smallest incisions, induced the least amount of astigmatism
As would intuitively be suggested, as the wound becomes smaller in size - from 12-14 mm down to 1.2-1.4 mm – the amount of surgically induced astigmatism is reduced.

5.3.2 Subluxed intraocular lens

The refractive results of displacement of an intraocular lens are known for many years (Lakshminarayanan, 1986). Using a modified Gullstrand schematic model eye, the authors have computed the amount of spherical and cylindrical errors that are induced due to the tilt and/or displacement of the intraocular lens. This refractive change can become a reason for repositioning and suturing the lens in place.

5.4 Post trauma

Trauma can cause refractive changes of the corneal and of the lens. In most but not all cases, the change is to the worst.

5.4.1 Effect on cornea

Akinci et al (2007) report of Trauma-induced astigmatism associated with regular astigmatic patterns in corneal topography in 14% of eyes suffering blunt ocular trauma. Induced astigmatism ranged from 1.75 D to 3.60 D.
Reddy et al (2007) report of a blunt trauma causing a large radial partial thickness corneal laceration at the vertical meridian, with several smaller lacerations in the periphery. Corneal topography revealed central flattening, and refraction changed from -3.50-1.50X175 to -1.50 only' reaching 20q20 vision with that correction. The corneal lacerations caused a spherocylindrical effect that luckily was consistent with good vision.

5.4.2 Effect on lens

Akinci et al (2007) report of Trauma-induced astigmatism associated with lens subluxation in 7% of eyes suffering blunt ocular trauma. Small and hard objects induced astigmatism significantly more frequently than others.

6. Presentation

Astigmatism presentation is both subjective, based on the patient's description, and objective, based on instrument output.

6.1 Signs and symptoms

An astigmatic eye produces blurred vision. When corrected with spectacles, the different refractive power in the two principal meridians may cause distortion of the image on the retina.

6.1.1 Visual acuity

Visual acuity is lower with uncorrected astigmatism. The effect on vision depends both on amount of astigmatism and pupil size. In an experimental setting (Kamiya et al 2011), with astigmatism of 1, 2 and 3 D, logMAR UCVA was 0.04±0.08, 0.09±0.09 and 0.16±0.16 for 1 mm pupils, -0.01±0.09, 0.12±0.15 and 0.33±0.24 for 2 mm pupils, 0.02±0.09, 0.20±0.19 and 0.46±0.30 for 3 mm pupils, 0.02±0.08, 0.24±0.20 and 0.48±0.21 for 4 mm pupils, and 0.08±0.10, 0.33±0.18 and 0.53±0.22 for 5 mm pupils, respectively. The variance of the data was statistically significant ($p=0.03$ for 1 D, $p<0.001$ for 2 D, $p<0.001$ for 3 D, analysis of variance). With-the-rule and against-the-rule astigmatism had similar effect.

6.1.2 Visual disturbance / discomfort

Visual discomfort from small amounts of astigmatism was examined (Wiggins et al 1992). The volunteers wore soft contact lenses, leaving between 0.50 and 1.00 D of residual astigmatism in each eye (mean = 0.68D). They were then examined using either full correction in a trial frame or a control lens (=0.12 D). Analysis of the data indicated greater reported visual comfort for the test lens pair over the control lens pair.

6.2 Visual quality

The optical performance of the eye is related to a few interconnected terms: the point-spread function (PSF), Strehl ratio, and retinal-image spot radius (Mihâltz et al 2011). The PSF of an optical system is the irradiance distribution of light from a point source projected onto the retina; it indicates the extent of blurring of the retinal image. The Strehl ratio is the ratio of the peak height of the PSF divided by maximum intensity of PSF in the diffraction-limited perfect eye. The Strehl ratio range is from 0 to 1; the greater the Strehl ratio, the better the quality of vision. Quality of vision can also be described by the minimum spot radius in the retina. Comparing groups of keratoconus eyes, subclinical keratoconus eyes and normal eyes, ocular aberrations were measured with a Hartmann-Shack sensor. The Strehl ratio significantly discriminated between the control group and the two ectatic groups, and the spot ratio separated each group from the other two.

6.3 Instrumentation

Our understanding of phenomena is channeled by the tools we have to measure them: in cataract, loss of visual acuity is easier to quantify than the change in the quality of life caused by the cataract. Visual acuity is therefore the parameter we turn to when considering surgery, although improving quality of life should be our real goal. Through this human property we use our instruments to define our understanding of the term "astigmatism".

6.3.1 Keratometry

The keratometer is used to approximate the refracting power of the cornea (BCSC 2008-2009). The central cornea can be thought of as a very powerful (about 250 D) convex spherical mirror. An illuminated object is placed in front of the cornea. A microscope is used to magnify the

image reflected from the corneal surface, and the radius of curvature of the corneal surface is calculated. The final step is to convert radius of curvature into an estimate of the cornea's dioptric refractive power. This step is prone to error, since the anterior corneal surface is measured, but the posterior surface is only estimated. Another drawback of the keratometer is that it measures the central 3 mm of the cornea, and not the entire surface.
The keratometer is used to measure the two main meridians of the cornea, The difference between these two results is the keratometric astigmatism. If the astigmatism is regular, the two meridians perpendicular to each other.

6.3.2 Retinoscopy

The streak retinoscope is a tool to determine objectively the spherocylindrical refractive error, as well as determine whether astigmatism is regular or irregular, and to evaluate opacities and irregularities (BCSC 2008-2009). The examiner adds sphere and cylinder lenses until all spherocylindrical refractive error of the eye is neutralized. Whatever irregularity in the light reflex that remains is irregular astigmatism, or in other nomenclature – high order aberrations.

6.3.3 Corneal topography

Corneal topography is similar in concept to conventional keratometry. However, unlike keratometry, that measures tow pairs of spots in the central 3 mm of the cornea, corneal topographers map the surface of the cornea, from close to the center out to 4 or 5 mm from the center (BCSC 2008-2009).
Most topographers are based on circular mires, similar to a Placido disc, consisting of many concentric lighted rings. The size and shape of the reflected images of the mires are the data, from which multiple calculations, similar to those behind the concept of the keratometer, are performed. The end result is a color map, graphically illustrating the corneal curvature in many thousands of spots on the corneal surface. Many topographers also calculate the SIM K (simulated keratometry) value, providing the power and location of the steepest and flattest meridians for the 3-mm optical zone
Different patterns of corneal topography have been described (Rabinowitz 1998): One (round) describes a spherical surface with no astigmatism. Two more (oval and symmetric bow tie) describe a spherocylindrical surface with no irregular astigmatism. All other patterns describe different amounts of irregularity: superior steepening, inferior steepening, irregular, symmetric bow tie with skewed radial axes, asymmetric bow tie with inferior steepening, asymmetric bow tie with superior steepening, asymmetric bow tie with skewed radial axes.

6.3.4 Corneal tomography

Scheimpflug photography and densitometric image analysis are very precise techniques for light scattering measurement and biometry in the anterior segment of the eye (Wegener & Laser-Junga, 2009). Commercial instruments based on the Scheimpflug photography princilple take multiple images of the cornea, all centered on the corneal apex. The front and back surface of the cornea are detected for each image, and 3 dimentional representation of the front and the back surfaces of the cornea are built. The total optical effect of the cornea, from both front and back surfaces, can be calculated.

6.3.5 Wavefront analysis and retinal raytracing

Wavefront analysis and retinal raytracing are used to measure the lower and the higher-order optical aberrations of the entire eye. Wavefront analysis is the study of the shape of light waves as they leave an object point and how they are affected by optical media (BCSC 2008-2009). An ideal optical system with no aberrations would produce a flat wavefront. Any aberration would distort the shape of the wavefront. There are different methods to measure the wavefront. In Hartmann-Shack aberrometry a single spot of light is lit on the retina, and the wavefront of the exiting light is calculated. This method is considered outgoing aberrometry. In Tscherning aberrometry the ingoing light passes through a mask of holes before entering the eye. The resultant array of spots on the retina is captured with a high-magnification camera, and the wavefront of the entering light is calculated. This method is considered ingoing aberrometry. Retinal raytracing is another example of ingoing aberrometry. Here a laser beam is used to scan across the pupil. At each laser beam position, the amount of deviation is measured, and the degree of aberration can thereby be calculated.

7. Conclusion

Astigmatism affects a large portion of people. Much of it is regular, correctable with spectacles or soft contact lenses. Other refractive irregularities, or high order aberrations, are partially or fully correctable with rigid contact lenses or refractive surgery.

The understanding of irregular astigmatism grew with the development of the field of refractive surgery. With instruments capable of manipulating tissue in the sub micron level, there is motivation to research and to treat. The future will bring more diagnostic devices and more treatment modalities, improving our ability to better treat refractive errors, including different forms of astigmatism.

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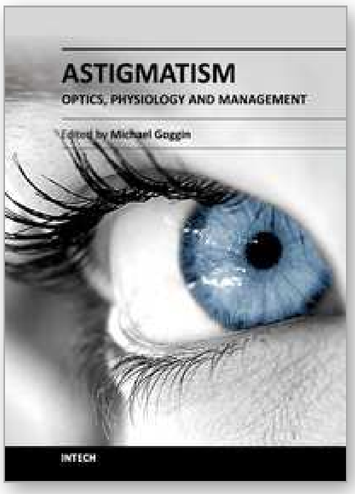

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This book explores the development, optics and physiology of astigmatism and places this knowledge in the context of modern management of this aspect of refractive error. It is written by, and aimed at, the astigmatism practitioner to assist in understanding astigmatism and its amelioration by optical and surgical techniques. It also addresses the integration of astigmatism management into the surgical approach to cataract and corneal disease including corneal transplantation.