Customized Laser Vision Correction

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Arthur B. Cummings
Editors

Springer

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Foreword

Laser refractive surgery has come of age. Refractive surgery delivers benefits across many dimensions—productivity, safety, convenience, lifestyle, economics and quality of life—and the impact of refractive surgery on the human experience can hardly be overstated. Several professions, ranging from first responders to athletes to military and television personalities, have adopted refractive surgery as a standard. Tens of millions of people have been treated. The elegance and precision of modern refractive surgery technologies are amazing.

Routine laser vision correction to treat refractive errors makes up the lion's share of corneal laser refractive surgery. Yet there are many eyes that may benefit from customized treatments that go beyond simply improving the refractive outcome. Sometimes these treatments are done to attempt optimizing optical performance; other times they are performed to eliminate irregularities in the corneal surface, and in some cases, customized treatments are performed to provide added depth of focus for presbyopia.

Customized laser vision correction has an interesting history starting with topography-guided treatments using the Bausch and Lomb Keracor 117 excimer laser to treat corneal irregularities in the early 1990s. Whole-eye aberrometer-guided treatments came into clinical use with the WaveLight laser platform, the Visx platform and the Bausch and Lomb Zy-wave treatments in the early 2000s. Early claims of achieving "super-vision" with aberrometer-guided treatments quickly gave way to the recognition that the main benefit of these treatments was that they generally induced less spherical aberration due to improved optical designs. A significant contribution to the aberrometry-guided technologies was to improve ablation profiles in the form of "wavefront-optimized" treatments with the WaveLight and other platforms, which have performed well and have stood the test of time.

Over the past decade, there is a trend for most laser platforms to migrate towards topography-guided treatments. Nidek, Schwind, Zeiss and Alcon WaveLight all have commercial platforms in current use for topography-guided treatments. When used for primary treatments, topography-guided treatments are most commonly used to reduce coma resulting from corneal asymmetry. When used for therapeutic treatments, topography-guided treatments are used to improve optics after prior surgery, or to treat pathology such as keratoconus.

Customized laser vision correction seems simple in concept—just regularize the cornea and leave it with a final curvature that will deliver the desired refractive outcome. In practice, the goal of simultaneously improving corneal shape while achieving reliable refractive outcomes has been elusive.

There are many considerations and these treatments can be complex. There are several steps involved in customized laser vision treatments. Challenges exist at nearly every step. Designing customized treatments requires understanding of the diagnostic equipment, potential artefacts, corneal physiology, depth limits, optics and laser parameters, placing a significant burden on the surgeon during surgical planning. Technologies that support customized treatments are still evolving and have not yet been fully automated.

Refractive surgery represents a turning point in the human experience; it provides the first example where a congenital defect of fundamental importance can be corrected on a mass scale. The past decades have seen refractive surgery evolve from concept into practice, with improvements in predictability, safety, scope and impact. The next era will see refractive surgery proliferate and assume the role as primary care for vision correction. Challenges exist—affordability, delivery systems, personnel, acceptance and others—yet each of these challenges will be met as the field scales to meet the demand. The question is not if, but when.

To reach full adoption, refractive surgery must establish safety levels comparable to the airline industry. In the rare instances where complications occur, customized laser vision correction will provide a key solution.

This book describes the essential concepts behind customized treatments. The evolution of thought in these treatments is a testament to the brilliance, creativity and determination of those who have contributed to the field, with the editors and authors of this book among them. We owe them a debt of gratitude for their ongoing work and commitment to ongoing innovation in refractive surgery.

Arizona, USA Guy M. Kezirian

Preface

This book with contributions from across the globe by authors who are passionate about refractive surgery and specifically customized LASIK is designed to hopefully ignite your passion, increase your knowledge and understanding and fuel your curiosity. As the saying goes, the more we learn, the less we know. This field is standing on the shoulders of giants and is going to grow more than any of us realize currently. In years to come, refractive surgery may become a rite of passage as do orthodontic braces for misaligned teeth. It is our job to make LVC so safe that it is no longer questioned and so effective that everybody wants it, and we need to make it available to more people. We are immensely grateful to our colleagues who shared their expertise in this book.

When I hear a colleague say that LASIK or PRK is easy and anyone can do it, I am reminded that our patients deserve more. They deserve a surgeon who takes this very seriously indeed. A surgeon who knows that they have good vision with their spectacles and realizes that this is an area where surgical complications are simply not tolerated. If you are not nervous doing a refractive procedure, including something as controlled as LASIK, you are not taking it seriously enough. We are treating people who have healthy eyes and who have other options. If we decide that laser vision correction is the best option for them, we had better do the very best job that we can.

There are many things that I am grateful for: my wife and my sons, my late parents and my immediate family and friends. I'm grateful for good health. Among all the other things in my life that I am grateful for is the fact that I am an ophthalmologist by profession. Even more so, I am grateful that I got into the area of refractive surgery. As ophthalmologists, we have a wonderful opportunity to improve people's lives daily. Restoring sight, preserving sight and, for refractive surgeons, correcting sight.

Customized Laser Vision Correction underlines the fact that we now have tools to improve vision to beyond what nature gave us, even with the help of glasses and contact lenses. It has also given us the tools to improve on outcomes where things did not go perfectly well with vision correction surgery and restore the quality of vision once more. I hope that you enjoy this book as much as we enjoyed writing and editing it. I hope that you learn as much as we did too in the process.

Dublin, Ireland Arthur B. Cummings

Making a Difference

In our life, there is always a difference: a difference between being beautiful and being captivating and between being good and being outstanding. That is simply the difference between science and art; however, joining both is mastery.

Correcting vision is a science but drawing vision is an art. Amongst options of vision correction, laser vision correction (LVC) is the most popular. Over the last few years, laser ablation profiles were developed to achieve very good vision, but this is not the mastery today. The mastery today is how to treat corneal irregularities and higher order aberrations (HOAs) to improve the quantity (science) and quality (art) of vision and that is what is known by customized LVC.

Artists look at a scene from different angles and create different dimensions for the scene, and so is customized LVC. There are different subtypes of this type of treatment, and they all aim at reducing corneal irregularities and patient's symptoms. Corneal wavefront-guided treatments manipulate corneal HOAs. Ocular wavefront-guided treatments manipulate the whole-eye HOAs. Topography-guided treatment and Contoura Vision correction deal with irregularities in terms of corneal elevations. Q-guided treatment deals with corneal asphericity. Raytracing-guided treatment is the latest promising technology that deals with all the previous aspects in addition to eye dimensions and refractive error.

Since I started practising ophthalmology in 1996, I decided to add something to ophthalmology, not only as a physician who is keen to bring the best technology to his patients, but also as a colleague who is keen to bring the best knowledge to his colleagues. This dream became a reality when I published my first book on corneal topography in 2008. I cannot describe how much happiness I felt when I saw my colleagues could read and understand topography accordingly. That motivated me to publish more books about refractive surgery and keratoconus management, and here, I must stop with respect for the support given by my wife and my children for the time they give me, and sure will not forget the virtue of my parents who implanted in my soul tenderness and helping others.

This book is different in many ways. Mainly, it is thanks to the big names of the contributors who are all regarded as global experts in this field. This book is the only book currently available that addresses this topic of customized laser vision correction. It follows a systematic and academic step-by-step methodology. Each subtype is discussed in terms of indications, contraindications, principles of the relevant laser ablation profile and, most important, how to build the laser profile for each case.

We tried to make this book a practical guide in clinical daily practice by drawing scientific guidelines in this art of treatment. We are very grateful to our fellow authors for contributing to this book and sharing their knowledge and experience for the benefit of us physicians and our patients, thereby enhancing our vision and our lives.

Damascus, Syria Mazen M. Sinjab

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Abbreviations

μm	Micrometer (micron)
AB/IS	Asymmetric bowtie inferior steep
AB/SRAX	Asymmetric bowtie with skewed radial axis index
AB/SS	Asymmetric bowtie superior steep
ATR	Against-the-rule
BFE	Best fit ellipsoid
BFS	Best fit sphere
BFTE	Best fit toric ellipsoid
BVD	Back vertex distance
CCT	Central corneal thickness
CDVA	Corrected distance visual acuity
CR	Cycloplegic refraction
CTK	Central toxic keratopathy
CTSP	Corneal thickness spatial profile
Custom-Q	Asphericity-guided
CWF	Corneal wavefront
CWG	Corneal wavefront-guided
CXL	Corneal cross linking
D	Diopter
DEq	Dioptric equivalent
DLK	Diffuse lamellar keratitis
ECD	Ectatic corneal disease
EKR	Equivalent K-reading
Epi-LASIK	Epipolis laser in situ keratomileusis
FDA	Food and drug administration
Femtolasik	Femtosecond laser in situ keratomileusis
FFKC	Forme fruste keratoconus
HOA	High order aberration
I	Inferior
IOL	Intraocular lens
IS	Inferior steep

K_1	Keratometric reading (K-reading) on the flat meridian
K_2	Keratometric reading (K-reading) on the steep meridian
K_c	Central K-reading
KC	Keratoconus
KG	Keratoglobus
K_{max}	Maximum K-reading
K_{ref}	Reference K-reading
LASEK	Laser subepithelial keratomileusis
LASIK	Laser in situ keratomileusis
LKP	Lamellar keratoplasty
LOA	Low order aberration
LVC	Laser vision correction
MFIOL	Multifocal intraocular lens
MR	Manifest refraction
MRc	Corrected manifest refraction
MTF	Modulation transfer function
ODP	Objective spherocylindric dioptric power
OWF	Ocular wavefront
OWG	Ocular wavefront-guided
PIOL	Phakic intraocular lens
PKP	Penetrating keratoplasty
PLK	Pellucid-like keratoconus
PMD	Pellucid marginal degeneration
PMT	Post-mydriatic test
PRK	Photorefractive keratectomy
PSF	Point spread function
PTI	Percentage thickness increase
PVA	Potential visual acuity
QS	Quality specification
RGP	Rigid gas permeable
RI	Refractive index
RK	Radial keratotomy
RLE	Refractive lens exchange
RMS	Root mean square
RS	Reference surface
RT	Ray tracing
S	Superior
SA	Spherical aberration
SB	Symmetric bowtie
SB/SRAX	Symmetric bowtie with skewed radial axis index
SBK	Sub-Bowman keratomileusis
SD	Standard deviation
SE	Spherical equivalent
Simk	Simulated K-reading
SimLC	Simultaneous laser correction

SMILE	Small incision lenticule extraction
SR	Strehl ratio
SS	Superior steep
T-CAT	Topographic computer-assisted treatment
TCRP	Total corneal refractive power
TCT	Thinnest corneal thickness
TE TG-PRK	Trans-epithelium topography-guided photorefractive keratectomy
TE-PRK	Trans-epithelium photorefractive keratectomy
TG	Topography-guided
TG-PRK	Topography-guided photorefractive keratectomy
TL	Thinnest location
TMR	Topography-modified refraction
TNP	True net power
TransPRK	Trans-epithelial photorefractive keratectomy
WFG	Wavefront-guided
WFO	Wavefront-optimized
WTR	With-the-rule

Chapter 1
Introduction to Astigmatism and Corneal Irregularities

Mazen M. Sinjab

Abstract A good knowledge of the geometry of the human eye in general and the cornea, is important for customized laser vision correction (CLVC). The difference between optical, visual, pupillary, and achromatic axes, in addition to line of sight, angles kappa, alpha and lambda, is important for understanding the basics of CLVC. The same can be said about corneal dimensions, zones, shape and power.

CLVC aims at improving both quality and quantity of vision by correcting the lower order aberrations (refractive errors) and the higher order aberrations (HOAs). The HOAs are induced by irregularity and asymmetry in the optical system of the eye. To understand the HOAs and their role in the management, definitions, classifications, and etiology of astigmatism, particularly the irregular type, should be understood.

Irregular astigmatism is evaluated subjectively and objectively. The evaluation starts from suspicion and goes through subjective refraction before it ends with ancillary tests, the most important being corneal topography/tomography and aberrometry. The former is essential to confirm the diagnosis, study the tomographic patterns of corneal maps and define ectatic corneal diseases (ECDs).

Objective corneal dioptric power (ODP) is a new concept. It measures the potential power of the cornea in reference to an average K reading of the normal population. This concept is based on understanding the factors affecting corneal power measurement and the types of corneal power maps. Calculating the ODP helps in understanding how the laser ablation profile works.

Keywords Optical axis · Visual axis · Pupillary axis · Achromatic axis · Line of sight · Angle kappa · Angle lambda · Angle alpha · Astigmatism · Topography · Tomography · Keratoconus · Pellucid marginal degeneration · Pellucid-like keratoconus · Keratoglobus · Ectasia · Forme fruste keratoconus · Keratoconus suspect · Posterior keratoconus · Enantiomorphism

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1.1 The Optical System of the Human Eye

The optical system of the human eye is composed of four main non-coaxial optical elements (anterior and posterior corneal and lens surfaces), the pupil, and the retina, which is aplanatic to compensate for the native spherical aberrations and coma through its non-planar geometry [1]. Although, the optical surfaces are aligned almost co-axially, the deviations from a perfect optical alignment results in a range of axes and their inter relationships (Fig. 1.1). This leads us to the following definitions [1]:

The optical axis: It is the axis containing the center of curvatures of the optical surfaces of the eye. It can be recognized by the Purkinje images I, II, III, and IV namely of the outer corneal surface (I), inner corneal surface (II), anterior surface of the lens (III) and the posterior surface of the lens (IV). If the optical surfaces of the eye were perfectly coaxial, these four images would be coaxial, which is seldom observed.

The visual axis: It is the line connecting the fixation point with the foveola, passing through the two nodal points of the eye, but not necessarily through the pupil center.

The pupillary axis: It is the normal line to the corneal surface that passes through the center of the entrance pupil and the center of curvature of the anterior corneal surface.

The line of sight: It is the ray from the fixation point reaching the foveola via the pupil center.

The achromatic axis: It is defined as the axis joining the pupil center and nodal points.

Angle Alpha: Angle formed at the first nodal point by the eye's optical and visual axes.

Angle Kappa: Angle between pupillary and visual axes.

Angle Lambda: Angle between pupillary axis and the line of sight.

The refractive power of the human eye emerges mainly from the cornea and the crystal lens. In emmetropia, corneal power ranges from 39 to 48 diopters (D) (average 43.05D) [2], while the power of the crystalline lens is between 15 and 24D (average

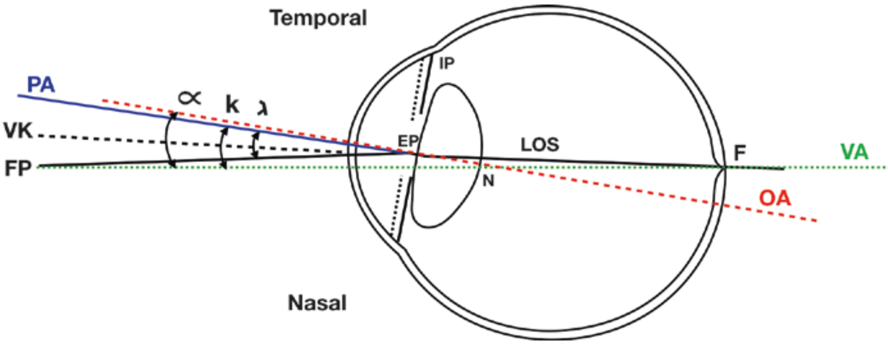

Fig. 1.1 Optical surfaces and axes in the human eye

19.11) [2]. The refractive media in the human eye are [2]: tear film (n = 1.336), cornea (n = 1.376), aqueous humor (n = 1.336), crystalline lens (n = 1.406), and vitreous humor (1.336); where n is the refractive index of the media measured relatively to air (n = 1.000). The important features determining the dioptric power of these media are the radius of curvature, the refractive index, and the distance between various interfaces.

1.2 Corneal Geometry

The cornea is composed of two surfaces separated by corneal substance. The anterior surface is coated with the tear film, and together form one refractive surface separating air from corneal substance. The posterior surface separates corneal substance from aqueous humor. The shape of both surfaces is defined as: An aspheric prolate, toric, asymmetric conoidal shape. Each of the previous expressions will be explained in detail in the following paragraphs.

1.2.1 Corneal Dimensions

Corneal dimensions include diameters, meridians, radii of curvature, corneal zones, corneal thickness, corneal shape, corneal power, and geometric landmarks.

(a) Diameters:

The cornea is not a part of a perfect sphere. The sclero-corneal junction (base of the cornea) is an *ellipse*. The vertical corneal diameter is 10.6 mm on average, whereas the average horizontal corneal diameter is 11.7 mm [3].

(b) Meridians:

The normal adult cornea has two meridians that are 90° apart. Due to the elliptical base of the cornea at the sclero-corneal junction, the vertical diameter is generally smaller than the horizontal one, meaning that the vertical meridian is steeper (smaller radius of curvature) than the horizontal one (greater radius of curvature). Due to this difference, the cornea is considered as *toric*. This toricity is responsible for corneal astigmatism. In younger eyes, this toricity is represented as with-the-rule astigmatism (WTR), where the vertical meridian is steeper than the horizontal one [4, 5]. This reverses with age, causing against-the-rule astigmatism (ATR) [6].

(c) Radius of curvature:

The cornea has two surfaces, anterior with an approximate radius of 7.8 mm, and posterior with an approximate radius of 6.5 mm [3]. These two radii are for the central (axial) zone of the cornea. As we move to the corneal periphery, the radii increase, indicating a flatter corneal periphery. The normal cornea flattens progressively from center to periphery by 2–4 diopters (D), with the nasal area flattening

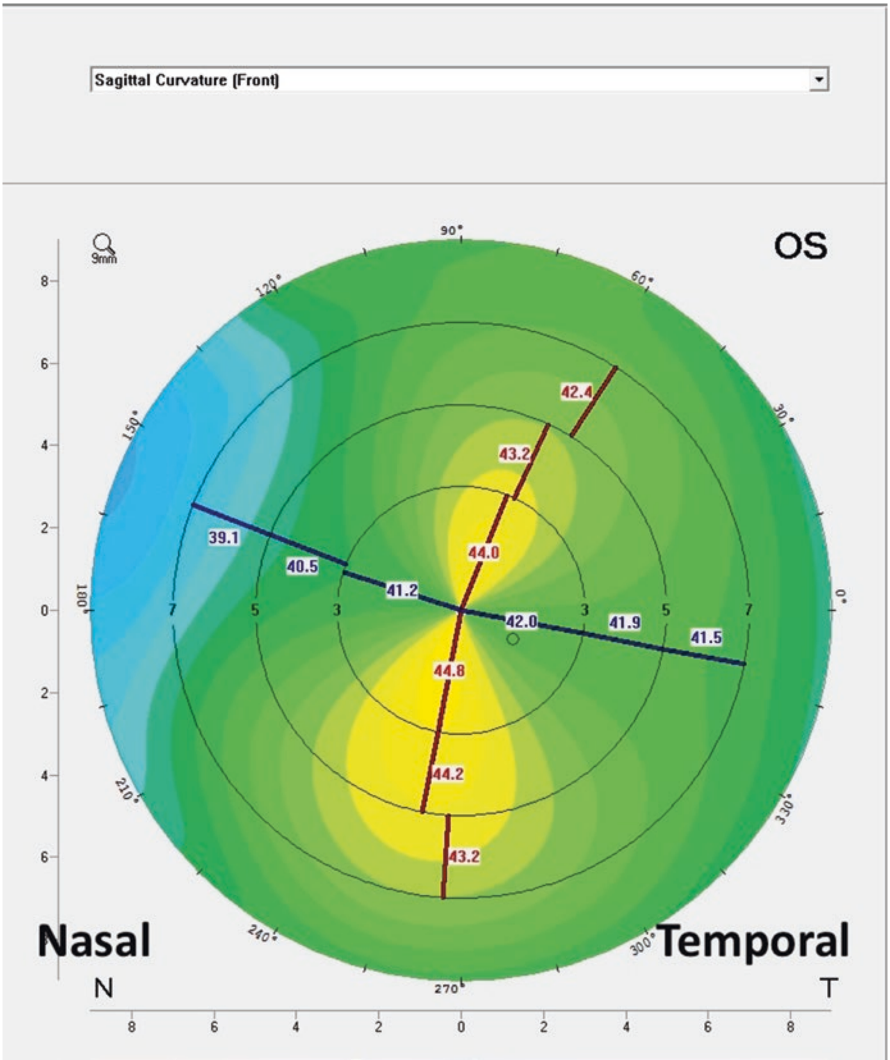

Fig. 1.2 The curvature map of the anterior corneal surface

more than the temporal area, and this is shown on the curvature map as the nasal side becoming blue (flat) more quickly (Fig. 1.2).

(d) Corneal Thickness:

Due to the difference in radius between the two corneal surfaces, the cornea is thinner in the central zone than at periphery. There are two important values in corneal thickness: central corneal thickness (CCT) and thinnest corneal thickness (TCT). Both will be discussed later in this chapter.

1.2.2 Corneal Zones

Clinically, the cornea is divided into zones that surround fixation and blend into one another:

(a) The central zone (central 1-2 mm): It overlies the pupil and is responsible for high definition vision. The central part is almost spherical and is also called the apical or axial zone [7].
(b) The para central zone (3-4 mm): It has a doughnut shape with an outer diameter of 7–8 mm. It represents an area of progressive flattening towards the third zone [7].

    The central and para central zones are responsible for the refractive power of the cornea, and are used for contact lens fitting.
(c) The peripheral zone: It is also known as the *transitional zone* [7]. This zone is asymmetrically flatter than the central zone. The nasal and superior segments are flatter than the temporal and inferior ones [2].
(d) The limbal zone: It is adjacent to the sclera and is the area where the cornea steepens prior to meeting the sclera at the limbal sulcus [7].

Being steeper in the center and flatter at periphery gives the cornea what is known as a "*prolate*" aspheric shape [8].

1.2.3 Corneal Shape

Corneal shape is "conoidal" (Fig. 1.3). It is a composition of an ellipse, asphericity and asymmetry [8–16]. From a meridional viewpoint, the cornea is "Ellipsoid", which is the source of corneal astigmatism. From the zonal viewpoint, the cornea is "aspheric "because the radius of curvature differs between the center and the periphery. From a sectorial viewpoint, the cornea is asymmetric because the nasal sector is usually flatter than the temporal sector.

Corneal asphericity is expressed by what is known as the "Q-value." The average Q value in the normal population is approximately −0.27 [17]. An abnormal Q value means abnormal corneal asphericity, the origin of corneal spherical aberrations. The Q value at which no spherical aberration is found on whole eye wavefront is −0.53 on average [18]. Asphericity and spherical aberration will be discussed in detail in Chap. 2.

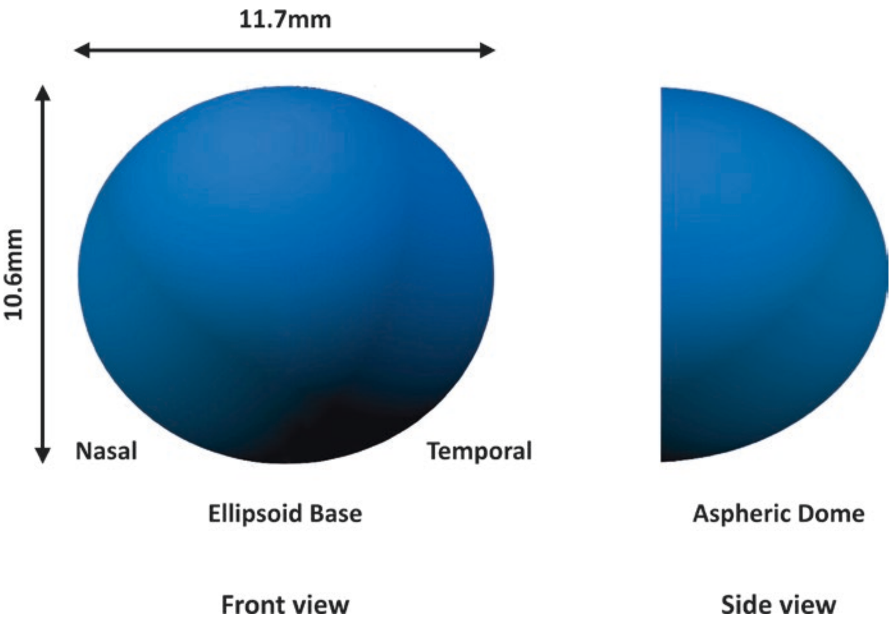

Fig. 1.3 The conoidal shape of the human cornea. The conoid is a composition of an ellipse, asphericity and asymmetry. Left: the base of the cornea is an ellipse because it has two different radii, and therefore two different diameters. The vertical diameter is usually smaller, which is the source of with-the-rule astigmatism. Right: the aspheric shape of corneal dome. Normal cornea is usually slightly prolate. Asymmetry comes from that the nasal sector of the cornea is flatter than the temporal sector

1.2.4 Corneal Power

The anterior corneal surface with its associated tear film layer plays a role of a convex refractive surface. Due to both its convexity and separation between two different media: air (smaller refractive index (RI); n = 1.000) and corneal substance (larger RI; n = 1.376), it encounters the most powerful refractive surface in the optical system of the eye. The refractive power of the central (apical or axial) zone of the anterior corneal surface is approximately 49D [2].

On the other hand, the posterior surface of the cornea is convex as well, but it acts as a negative concave surface because it separates corneal substance (larger RI; n = 1.376) from aqueous humor (smaller RI; n = 1.336). The refractive power of the posterior corneal surface is approximately −6.0D [2].

Moreover, corneal epithelium has an impact on corneal power. The shape of the epithelial layer is responsible for about 0.40D of astigmatism. The mean Q value is −0.20 ± 13.0 (0.06 to −0.60) with epithelium and − 0.26 ± 0.23 (0.07 to −1.51) without epithelium. In other words, the cornea is more prolate without the epithelium.

This fact has a clinical impact on laser vision correction (LVC) procedures, especially in surface ablation techniques [19].

There are different methods to measure corneal power that will be discussed later in this chapter.

1.2.5 Geometrical Landmarks

There are virtual landmarks of clinical importance in the cornea. They are the apex, thinnest location (TL), central K reading (K_c), maximum K-reading (K_{max}), and position of entrance pupil center and angle kappa.

(a) Corneal Apex: It is the geometric center of the cornea, or, in other words, the intersection of the rotational anatomical axis of the anterior corneal surface with this surface. The computer considers this point as the origin of coordinates, x for the horizontal and y for the vertical axes. The direction of x is from the patient's right to their left, and the direction of y is from the bottom up. Corneal thickness at this point is usually referred to as central corneal thickness (CCT). Depending on the technology used for measuring corneal thickness, the average CCT ranges from 534 to 575 μm [20–22]. All other landmarks are measured from the corneal apex. Therefore, the x and y coordinates of this point have a value of 0.00 (Fig. 1.4).

(b) Thinnest location (TL): It is the location of the thinnest point in the measured cornea. Corneal thickness at this point is usually referred to as thinnest corneal thickness (TCT). In an international multi-center study based on the Pentacam HR (Oculus Optikgeräte GmbH, Wetzlar, Germany) [23], the average TCT was 536 μm overall. Values less than 469 or 435 μm (−2 or − 3 SD, respectively)

Fig. 1.4 Main landmarks on the cornea: pupil center, pachy apex (corneal apex), thinnest location and K Max (Front). Pachy apex represents the origin of x and y coordinates of the other landmarks

would be expected in less than 2.5% or 0.15% of normal corneas, respectively. The X-coordinate averaged 0.44 mm temporally, and the Y-coordinate averaged 0.29 mm inferiorly in relation with corneal apex. Y-coordinates >1.0 mm inferiorly were found in less than 0.5% of normal corneas.

(c) Central K (K_c): It is the average central Sim-K reading on the anterior corneal surface. Normal central Sim-K measured by the sagittal map is <47.2D [24–27].

(d) Maximum K reading (K_{max}): this is the highest K reading on the anterior corneal surface. Interestingly, at this point in time, there is no normative data for K_{max}.

(e) Entrance pupil center position and angle kappa: Angle Kappa is defined as the angle between the visual axis (line connecting the fixation point with the fovea) and the pupillary axis (line that passes through the entrance pupil and perpendicular to corneal plane). Measuring angle kappa is very important in refractive surgery in terms of laser ablation centration and multifocal intraocular lens (MFIOL) implantation [28]. A large angle kappa is clinically significant as it may lead to alignment errors during photo ablation in LVC [29]. Decentration of ablation zones can lead to under correction [30] and irregular astigmatism [29]. In addition, a large angle kappa can lead to lens decentration in intraocular refractive surgery [29]. Decentration of intraocular lenses may cause photic phenomenon [31] and decreased lens effectiveness [32]. MFIOL implantation is contraindicated when angle kappa is >400 µm [29, 33].

Normal distribution in angle kappa was studied by using Orbscan II (Placido-based) and the Synoptophore. It was found that values of angle kappa measured by the Orbscan II were almost as twice as when measured by the Synoptophore [29, 34]. Based on Orbscan II, Hashemi, et al. [34] determined an average value of angle kappa of 5.46 ± 1.33° in Iranian adults with insignificant inter-gender difference. In another study, Gharaee H, et al. [35] determined an average value of 4.96 ± 1.38° in total, an average horizontal angle kappa of −0.02 ± 0.49 mm, and an average vertical angle kappa of −0.09 ± 0.32 mm.

In addition, studies reporting normative angle kappa values in different conditions found that angle kappa was significantly higher in exotropes than in esotropes or controls [36], and tended to be larger in the left eye than in the right eye [35, 36]. Moreover, there was a positive correlation between angle kappa and positive refractive errors [29, 34, 37], which can be explained by the negative correlation with the axial length of the globe [38].

Unlike Placido-based topographers, Scheimpflug-based tomographers cannot measure angle kappa. This raises the need to find a way to estimate this angle in Scheimpflug-based tomographers. However, the visual axis can roughly be considered as passing in between the entrance pupil centre and the geometrical center of the cornea (corneal apex), and might be half the distance. Therefore, in Scheimpflug-based devices, angle kappa can roughly be half values of x and y of entrance pupil centre coordinates.

1.3 Definitions and Classifications of Astigmatism

Astigmatism is a term that was first introduced by Thomas Young in the early 1800s [39]. It refers to the refractive error in which there is a difference in the power of refraction in different meridians. It occurs whenever any one of the refracting surfaces in the optical system assumes a toric shape. Therefore, it can be of corneal origin, intraocular origin, or both.

There are two types of astigmatism, regular and irregular.

1.3.1 Regular Astigmatism

In regular astigmatism, there are two principle meridians, one is of minimum power (minimum curvature or flattest), and the other is of maximum power (maximum curvature or steepest). The steepest and flattest meridians are perpendicular to each other [2].

On corneal tomography, regular astigmatism appears in a symmetric pattern known as "Symmetric Bowtie: SB," which consists of two symmetric segments, "a" and "b' (Fig. 1.5).

Based on corneal tomography and Zernike wavefront analysis, regular astigmatism is described by five criteria:

1. There is only one flat meridian and one steep meridian.
2. The two meridians are at right angles.
3. The gradient of power between the two meridians is similar in all sectors.
4. It induces astigmatic low order aberrations (LOAs) (Fig. 1.6).
5. It is corrected by a sphero-cylindric lens.

If the optical system has regular astigmatism, the image of a point source at infinity is not focused at one point, it is distributed between two principal linear images, one is generated by- and parallel to- the principal meridian of maximum power of refraction, and the other one is generated by- and parallel to- the principal meridian of minimum power of refraction. The interval that is bracketed by these two linear images is referred to as the interval of Sturm. Within this interval, a circle of least confusion is located at the plane where the vertical and horizontal meridians are equally defocused. Images generated by other meridians are distributed along the interval of Sturm (Fig. 1.7) [40].

Based on the relationship between the formed images and the retina (location-based), or on the position of the refracting meridians (meridian-based), regular astigmatism can further be sub classified into [2, 40]:

(a) Location-based:

- Simple astigmatism: when one of the two principal linear images falls on the retina.

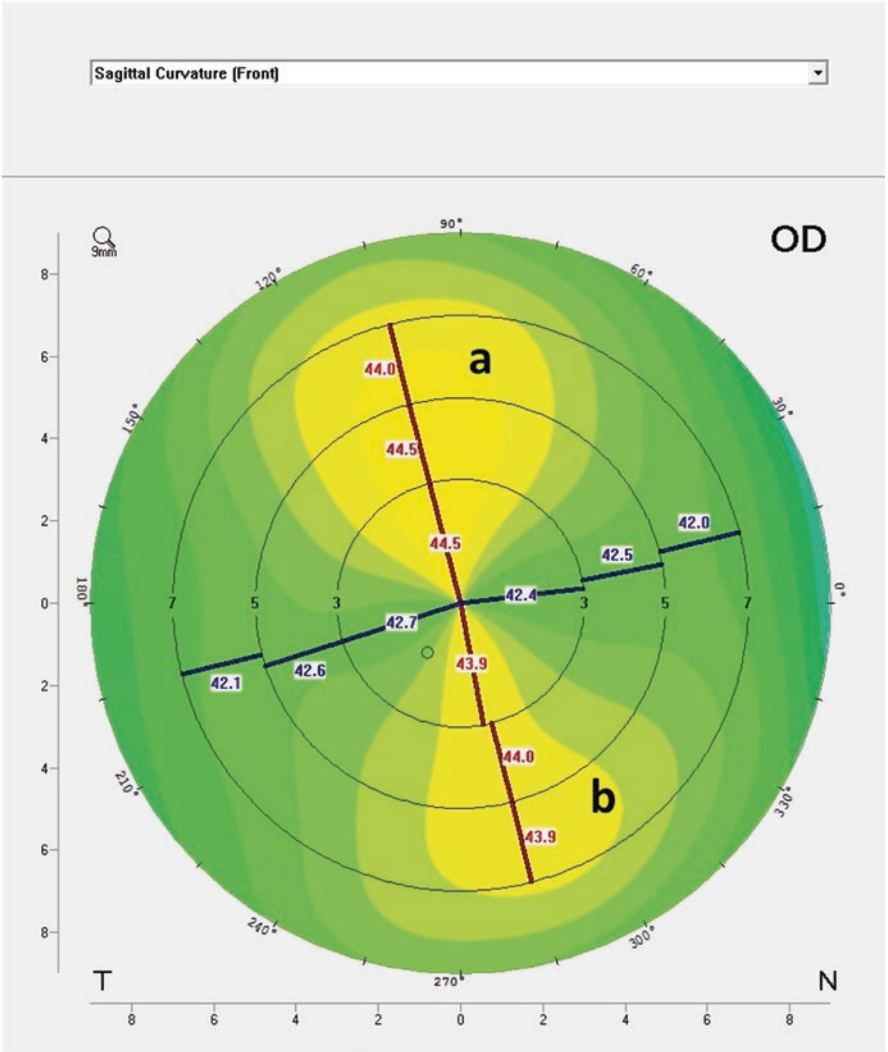

Fig. 1.5 Symmetric bowtie representing regular astigmatism

– If the other image falls in front of the retina, it is described by "simple myopic astigmatism." It induces astigmatic LOA (See Z_2^{-2} and Z_2^{2} in Fig. 1.6) and is corrected by a minus cylindric lens.
– If the other image virtually falls behind the retina, it is described by "simple hypermetropic astigmatism." It induces astigmatic LOA and is corrected by a positive cylindric lens.