Introduction

Even today, corneal topography remains one of the most misunderstood diagnostic tools for the clinician, despite its apparent simplicity, due to unrecognized complexities and oversimplification of formulas. In addition, several topographic/tomographic quantities are mislabeled by manufacturers, making it even more difficult for the clinician to understand. Similar quantities may carry different labels on different devices, and distinct quantities may carry the same label, further complicating interpretation.[1] This book is designed to offer clarity to the clinician. It is divided into three sections: Basics, Devices, and Applications. Chapters in the Basics section are foundational and applicable to all devices, independent of specific technology. Chapter 1 focuses on corneal surface geometry, including curvature. Chapter 2 highlights the important subtleties of how elevation data are interpreted. Chapter 3 illustrates how corneal thickness maps are advantageous over single point measures of central pachymetry. Finally, Chapter 4 describes the myriad of different indices for distinguishing keratoconic from normal corneal topography that are published in the literature to date.

The Devices section is not meant to be all inclusive, but rather to describe devices representative of a specific technology, as well as to further elucidate topographic principles by providing additional fundamental information relevant for multiple instruments. The Placido devices were the first to be developed and consist of a series of concentric rings, an image of which is reflected from the cornea surface, or more specifically, the tear film coating the surface. This class of technology provides data on the anterior surface of the cornea only. Since they were the first to be developed, Placido-based systems have also been the subject of the most studies of accuracy and repeatability. The 'Placido' itself has many manifestations – it can be a flat disk or large cone with a long focal length, or alternatively, a small cone that fits close to the eye with a shorter focal length. Thus, the small cone devices have greater coverage due to the proximity to the eye, but also greater sensitivity to errors of focus with a shorter working distance, requiring more sophisticated focusing techniques. The larger Placido's are further from the eye with less sensitivity to errors of focus, but the anterior corneal surface data may be shadowed by the nose or brow. The Keratron (Chapter 5), which is a small cone Placido device, was chosen to represent this class of technology. The development of the Orbscan (Chapter 6) was the first time clinicians were offered data from the posterior surface of the cornea and could appreciate that even though this surface contributes only about one tenth of the total corneal power, it has the potential to provide criti-

cal diagnostic information, as well as allow for the calculation of a pachymetric map. The Orbscan is based on scanning-slit technology and is combined with a novel rectangular Placido which produces rings on the cornea, but lacks information in the superior and inferior region. Two additional tomographic devices were later developed, based on Scheimpflug imaging with a rotating camera for reconstruction of the anterior segment. The Pentacam (Chapter 7) was the first Scheimpflug system to be introduced, and then the GALILEI (Chapter 8) which integrates Placido topography with dual Scheimpflug imaging. Other Scheimpflug systems have since been developed, but these two devices were chosen to represent this class of technology. Finally, the last two chapters in the Devices section describe systems with combined Placido topography and whole eye aberrometry, which was introduced in Chapter 5. The first is the OPD (Chapter 9) which determines whole eye wavefront aberrometry based on spatial dynamic skiascopy. The next is a recently introduced device called Discovery (Chapter 10) which offers simultaneous Placido topography and whole eye aberrometry via Shack-Hartman technology, for a fully integrated analysis.

Chapters in the Applications section describe only a sample of possible uses for corneal topography and tomography, with hundreds and perhaps thousands of papers in the literature. The first four chapters in this section were chosen to highlight the importance of both posterior surface and pachymetric data, in addition to anterior surface data, for optimal understanding of the consequences of refractive surgery and its affect on various clinical procedures and conditions. Posterior surface elevation maps have a greater tendency for misinterpretation than those of the anterior surface, due to smoothing produced by both the epithelium and the tear film. Features on the posterior surface are not masked by this smoothing action, and therefore may appear more prominent. Posterior 'high' areas may be incorrectly associated with pathology. Chapter 11 characterizes the post-refractive surgery appearance of anterior and posterior elevation, curvature, as well as pachymetry, and distinguishes potential iatrogenic ectasia from a normal post-operative response based on posterior surface analysis. In Chapter 12, corneal tomography is used to compare the swelling response of the normal cornea to that of the post-refractive surgery cornea. Both Chapters 13 and 14 discuss calculation of intraocular lens power in cataract surgery after refractive surgery, with Chapter 13 focusing heavily on the importance of the posterior surface in determining total corneal power. Chapter 15 offers a systematic analysis procedure for examining and characterizing topographic maps from a population, and Chapter 16 uses this procedure to compare two types of surgical approaches for Deep Lamellar Endothelial Keratoplasty.

Finally, Chapter 17 describes a fully topographic based system with a new approach for fitting contact lenses.

This book finishes with a Chapter on Classic References and Authors in Corneal Topography. It was included to allow appreciation of how long ago the analysis of corneal shape began, and how the development of the computer changed what used to be an arduous task into one that can be done in seconds. Dr. Robert B. Mandell developed many of the algorithms used in modern topographers beginning in 1961, but he did not have a computer.[2] He would capture images of rings and/or slits on 35-mm slides in order to project them onto the wall where he could trace the features by hand. Dr. Stephen D. Klyce had a computer, and developed the first color-coded topographic maps which are the basis of the displays in modern topographers,[3] as well as a scale still used today. Both of these scientists built on the foundations provided by Placido,[4] Helmholtz,[5] and Gullstrand.[6] Of note, the word 'Placido' in topography should always be capitalized since, like Goldmann tonometry, it is named after an individual, Antonio Plácido.

Misconceptions

Before beginning the Basics section, common misconceptions about corneal topography will be presented as preparation to aide in comprehension. These misconceptions are perpetuated in the literature, and even through reviewers, one of whom wrote: "Please use another word for power than power, since when clinicians hear the word power, they think of curvature." The ability to distinguish between curvature and power is critical to understanding corneal topography, where curvature maps are labeled in units of power (diopters) by the manufacturers. Another reviewer challenged the two-dimensional nature of curvature, which is fundamental to grasp what each map represents. Standardization[7] came after many devices were already on the market, so the confusion in nomenclature has persisted.

Axial Curvature vs Tangential Curvature

Curvature is a rate of change over a distance and is a two-dimensional (2-D) quantity. In technical terms, it is the rate of change of the tangent to a curve with respect to the arc length. For a three-dimensional (3-D) structure like the cornea, a plane of intersection must be used to define a 2-D curve for calculation. Thus, every point on the corneal surface has two principal curvatures, but there is only point for which two curvatures are generally defined clinically. The steep and flat corneal merid-

ians intersect at a point in manual keratometry, simulated keratometry (from topography), as well as manifest and cycloplegic refraction, each of which has its own associated central corneal surface point defining the optical reference axis. However, every other point of the cornea also has multiple curvatures. In topography, the meridians through the central reference point are used to define the direction in which curvature is calculated, shown in Figure 1A. Tangential curvature, also called local curvature or meridional curvature, is the calculation of curvature using classic equations along the meridians through the central axis.[8,9] Axial curvature, on the other hand, is the average of tangential curvature over a specified interval.[10] In other words; the magnitude of each point on an Axial map is the average of the Tangential curvature between the central reference point and that specific point. Therefore, all curvature extremes will be on the Tangential map, both high and low, an example of which is shown in Figure 1B.

When corneal topography was first introduced, the first map displayed was what is now known as the Axial map. This map was incorrectly labeled 'sagittal' at the time, which unfortunately has persisted in some modern devices. Sagittal curvature is defined in a direction perpendicular to tangential, as shown in Figure 1A, NOT the Axial curvature map of Figure 1B. In other words, the sagittal plane is along the direction of the rings in Placido topography, and tangential curvature is in a direction perpendicular to the rings. Thus, it is readily understandable how curvature in the sagittal direction cannot be calculated from Placido topography, since the rings are solid and nothing is changing in that direction. On the other hand, curvature can be calculated in the tangential direction, from ring to ring. The misconception originally developed when the curvature algorithms of early devices were generated from look-up tables compiled by measuring the position of the rings on steel balls of various curvature values. This technique is invalid when curvature is changing from ring to ring. In other words, curvature is a function of the distance between each ring, and what these early devices were calculating was the distance of the ring from the center. Serendipitously, the sagittal curvature of a rotationally symmetric surface like a steel ball, is equivalent to the Axial curvature based on the distance from the surface point to the reference axis along the normal in the tangential plane. Therefore, when the dioptric values measured on a rotationally-symmetric aspheric surface matched the formula for sagittal curvature, the misconception was born. Most corneas are NOT rotationally symmetric, and thus sagittal curvature is not measured, despite labeling by the device. At the time of writing this Introduction, no device on the market produces sagittal curvature. Several devices calculate mean curvature, which is the average of tangential
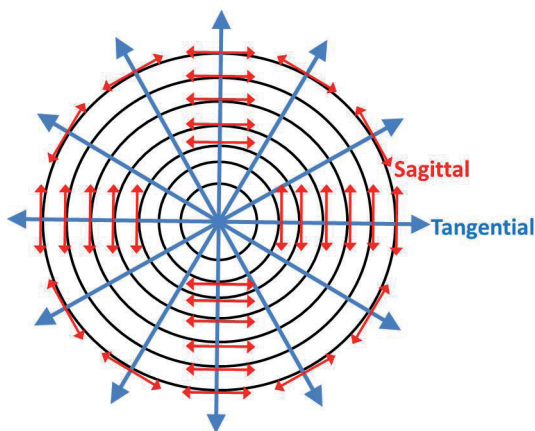
Fig. 1A. The tangential direction through the central reference axis is used for curvature calculation in topography and is illustrated by the blue arrows. The sagittal direction is perpendicular to the tangential and is illustrated by the red arrows. These exist at each point of intersection of a blue arrow with a black circle, but are only shown vertically and horizontally for clarity.
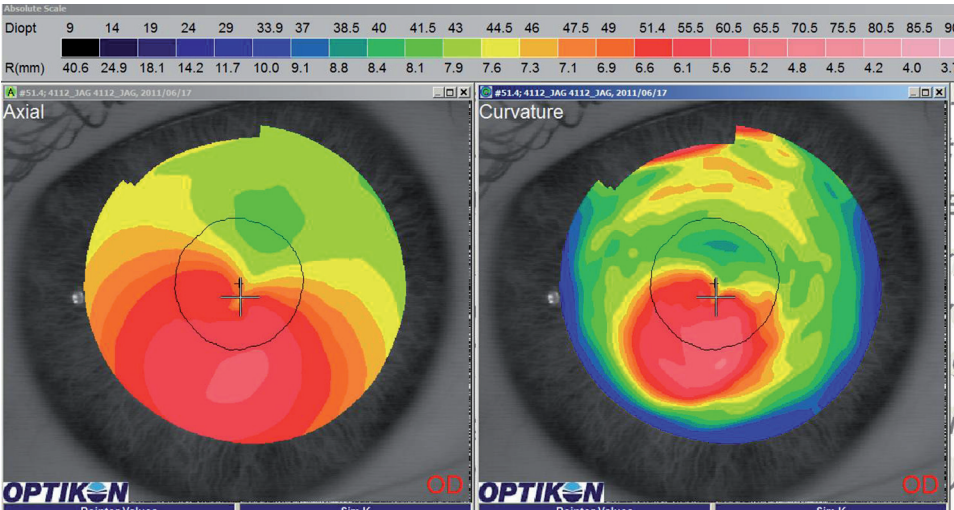

Fig. 1B. The Axial map is on the left and Tangential map is on the right. Note that for both maps, curvature in the tangential direction is calculated. The Axial map represents a running average of the Tangential map, such that the extremes, both high and low, are present on the Tangential map.

and sagittal curvatures. However, sagittal curvature is not calculated as a stand-alone map.

Kmax, or the value of maximum curvature will be *different*, depending on whether it is calculated on the Axial or Tangential map. It will be lower in magnitude on the Axial map and higher on the Tangential map. However, it is generally not specified which map

is used to determine 'maximum curvature'. Remember, if the Axial map is used, it is not the maximum curvature, since the Axial map is a running average of the Tangential map. An additional problem is that it is NOT advisable to use a single point for a 'maximum' value, especially in keratoconus, since it will likely be associated with high variability. A regional average around the maximum value would be less variable and better able to track changes in curvature.

In summary, the Axial map provides a global indication of corneal shape, and the Tangential map provides the specific details. They are identical in the center, and diverge moving from center to periphery. The Tangential map is inherently noisier than the Axial map, due to its second derivative nature. This causes some clinicians to prefer the Axial map since it is more robust. However, despite the noise, the Tangential map shows the details of the corneal curvature profile which cannot be accomplished with an Axial map. According to Tukey, a Princeton statistician:[11] '… when the right thing can only be measured poorly, it tends to cause the wrong thing to be measured, only because it can be measured well. And it is often much worse to have a good measurement of the wrong thing – especially when, as is so often the case, the wrong thing will IN FACT be used as an indicator of the right thing – than to have a poor measurement of the right thing.'

Elevation vs Curvature

Unlike curvature, elevation must have a reference from which to measure. As an analogy, the altitude of an airplane can be measured from the ground, or from sea level. Which would you prefer to know if you were a pilot? The answer is that both are important. A pilot needs to know the altitude above the ground so that the airplane does not crash into something, like a mountain. However, knowledge of the altitude above sea level is also important since it affects the performance of the airplane. The position of the airplane does not change, but the altitude requires a different reference depending on the application. In a similar manner, elevation topography can be referenced to a plane, to a sphere, or to an asphere. None of these are wrong; they simply have different applications and/or interpretations. Most commonly used is the 'best-fit' sphere (BFS), which subtracts the average curvature of the cornea. Approximately half of the sphere fits above the cornea and half of it fits below the cornea. The elevation with respect to the BFS has many practical uses. However, for some applications, like programming an excimer laser with an ablation profile, this map is not useful, since tissue cannot be added, only subtracted. The term 'best-fit means a mathematical algorithm is used to generate the sphere. Therefore, if a user-de-

fined sphere is chosen, it is no longer best-fit and no longer represents the average curvature of the cornea in the region over which the sphere is fit. It is *incorrect* to state, 'I chose my own best-fit sphere'. Also, if the pre-operative BFS value is imposed on the post-operative posterior elevation map, it is not best-fit and the comparison between pre and post-op is compromised, just as the comparison is compromised between pre and post-op with different reference spheres. The optimal technique to compare pre and post-op elevation maps is to fit one surface to the other, and then examine the regions in which they differ, as described in Chapter 11. For this approach, no reference is needed. The BFS is convenient in that the reference has a constant radius of curvature. If another reference is chosen, some of the shape of the cornea is buried in the reference and may affect interpretation. For example, an elevation map with a best-fit toric asphere reference will not demonstrate astigmatism in the map, and the user will need to examine the reference for astigmatic information.

Some pearls for interpreting elevation maps can be seen in Figures 2A and 2B. A central high area has greater curvature than the BFS, as shown in the anterior elevation map of Figure 2A. A central low area is flatter than the BFS, as shown in the anterior elevation map of Figure 2B. Note that despite negative values in the low area, this central zone is NOT concave. It is still the highest point on the map, but it is below the sphere. A peripheral high area is flatter than the BFS, since it is falling away from the center more slowly, and is shown in the posterior elevation map of Figure 2A. A peripheral low area has greater curvature than the BFS, since it is falling away from the center more quickly as shown in the posterior elevation map of Figure 2A.
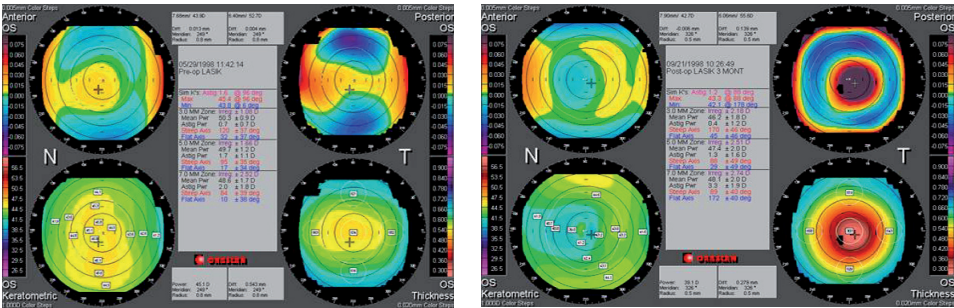

Fig. 2. For both Quad maps (A) on the left, and (B) on the right, the anterior elevation is upper left, and the posterior elevation is upper right. Axial curvature is lower left and pachymetry is lower right. The Quad map on the left is an astigmatic patient, and the Quad map on the right is a patient after refractive surgery.

Power vs Curvature

Power describes function and curvature describes shape. These are distinct quantities, and yet they are often used interchangeably. Diopters quantify corneal curvature, and yet these are units of optical power. This dates back to Helmholz[5] who discussed 'diopters of curvature' in his Treatise. The analogy is appropriate in the center of the cornea, which can be considered the 'paraxial' region (near the central axis), which is where keratometry is measured and the region to which Helmholz referred. In the paraxial region, power and curvature are directly proportional such that if curvature increases, optical power also increases and vice versa. This is due to the small angle of incidence of incoming rays of light in the paraxial region, so that minimal refraction occurs. However, this relationship is no longer valid outside of the central cornea where topography measures. As curvature *decreases* from the center to the periphery in a normal cornea, power *increases* due to the increasing angle of incidence between an incoming ray of light and the corneal surface.[12] Thus, a larger angle of incidence with subsequent greater refraction occurs, resulting in greater power. The definition of spherical aberration is a change in the power from center to periphery, driven by this changing angle of incidence. A spherical surface does NOT focus all light to a point.

The ONLY topographic map that represents corneal power is one where a Snell's Law refraction is used to calculate the dioptric values displayed. On the various devices, this is called 'Optical Power' or 'Refractive Power' or 'Ray Traced' or something that indicates Snell's Law has been utilized. Axial curvature is often *mislabeled* as 'Axial Power.' Tangential curvature is often *mislabeled* as 'Tangential Power.' Do not be fooled! Figure 3 shows the same ellipsoidal surface with 0.5 eccentricity (e), comparing diopters calculated with a Snells' Law refraction, Axial Diopters and Tangential Diopters. Note the paraxial region is where they are all the same color. Outside of this central region, the dioptric values diverge – for the two curvature maps in the same direction. However, for the refractive power map, the direction is opposite. As curvature *decreases*, power *increases*.

There is an additional complication in the inappropriate use of power and curvature interchangeably. In the early days of corneal topography when the devices only measured the anterior corneal surface, it was decided to use the keratometric formula to convert radius of curvature in mm to diopters over the entire cornea, well beyond what is encompassed by the paraxial region. Keratometry models the cornea as a single refracting surface with a calculated index of refraction that takes into account the negative power of the posterior corneal surface. The specific anterior curvature, posterior curvature, and pachymetry values of the Gullstrand eye model[6] were
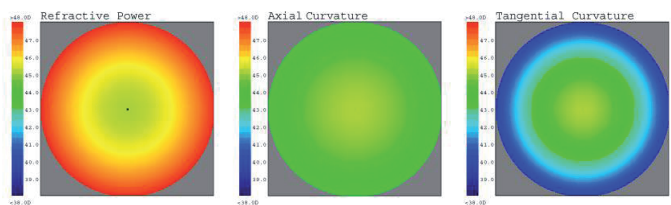
Fig. 3. All three maps are calculated from the same ellipsoidal surface with 0.5 eccentricity. On the left is a power map with a Snell's Law refraction at the surface, and shows increasing power from center to periphery. In the middle is an axial curvature map and shows decreasing curvature from center to periphery. On the right is the tangential curvature map which shows greater decrease in curvature from center to periphery. All three maps show the same dioptric value in the center, which defines the paraxial region for interpreting power. Outside of this region where the colors deviate from the power map on the left, the paraxial assumption is invalid and the dioptric values decrease on the curvature maps.

used to determine the index of refraction (1.3375) which would produce the same focal plane as when modeled with both an anterior and posterior surface. This produced an assumed ratio between anterior and posterior curvature. With the introduction of the Orbscan that could measure the posterior surface, the question of dioptric labeling was raised. It was decided to attempt to represent power in the center of the posterior surface, so that the conversion from radius of curvature to diopters used the difference in index of refraction of aqueous (lower index of refraction) minus cornea (higher index of refraction) as the numerator, making it negative. Certainly, the power is negative since in moving from a higher index material (cornea) to a lower index material (aqueous), the refraction causes the light to diverge rather than converge. However, negative curvature implies concavity. The result is that a curvature map of the convex posterior surface is negative. In addition, the Tangential curvature of the anterior surface cannot be easily compared to the posterior surface curvature, since the scaling of the numerator is different. For example, a 7-mm anterior surface would be 48.2 D if the keratometric index of refraction (1.3375) is used. The same surface would be 53.7 D if the index of refraction is of the cornea is used (1.376). However, if the *posterior* surface had a radius of curvature of 7-mm, its dioptric value would be -6.1 D. All of these different dioptric values are associated with the same radius of curvature, depending on the conversion factor used. The problem is that all of these maps overall are curvature maps which cannot be easily compared. The exception is in the very center where the region can be considered paraxial and thus representative of power.
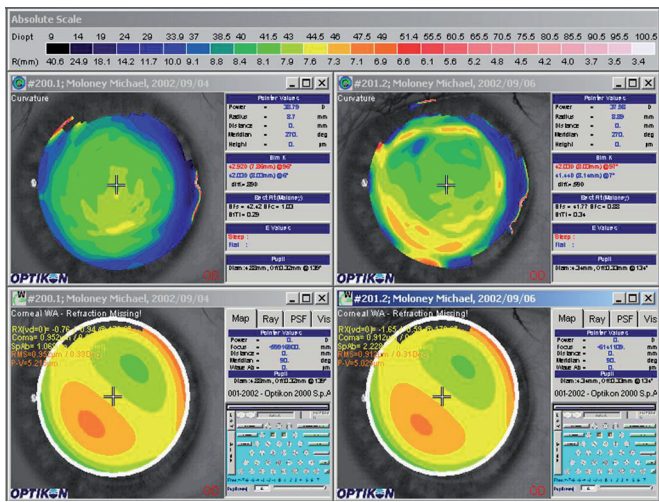
Fig. 4. The top row shows Tangential curvature maps and the bottom row shows the corresponding corneal wavefront maps with only third order coma selected for display. The cornea on the left is normal and the cornea on the right has had refractive surgery. The curvature maps are quite distinct and yet the third order coma is nearly the same, showing that it is nonspecific.

Topographic Analysis vs Wavefront Analysis

Topography represents shape and wavefront represents function. Ocular wavefront analysis provides information concerning the optics of the entire eye as a whole. A list of aberrations and their relative magnitude is produced for the user. However, no information is provided regarding the source of an aberration in terms of the specific surface (*i.e.*, cornea vs lens), or even the location of a feature on that surface which generates the aberration. Corneal wavefront analysis can be derived from corneal topography by ray tracing through the measured surface and calculating the wavefront produced by the cornea alone. The same limitations apply that the source of an aberration cannot be pinpointed on the corneal surface. For example, Figure 4 shows two corneal topographies with the same magnitude of third order coma. Yet, one map is a normal topography, and one is from a patient who has had myopic refractive surgery. Only topography can show features of the corneal surface which produce aberrations when light passes through that surface and propagates through the cornea.

It is important to remember that 100% of the eye's aberrations *induced* by refractive surgery are produced by the cornea. The wavefront map is like a snapshot in time, illustrating only the pre and post-operative state. The topography is necessary to determine what corneal features produced the measured aberrations.

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