REVIEW ARTICLE

Technologies for Anatomical and Geometric Characterization of the Corneal Structure and Anterior Segment: A Review

David P. Piñero¹,²,³

¹Department of Ophthalmology (Oftalmar), Medimar International Hospital, Alicante, Spain, ²Foundation for the Visual Quality (FUNCAVIS), Fundación para la Calidad Visual, Alicante, Spain, and ³Department of Optics, Pharmacology and Anatomy, University of Alicante, Alicante, Spain

ABSTRACT

Corneal and anterior segment imaging techniques have become a crucial tool in the clinical practice of ophthalmology, with a great variety of applications, such as corneal curvature and pachymetric analysis, detection of ectatic corneal conditions, anatomical study of the anterior prior to phakic intraocular lens implantation, or densitometric analysis of the crystalline lens. From the Placido-based systems that allow only a characterization of the geometry of the anterior corneal surface to the Scheimpflug photography-based systems that provide a characterization of the cornea, anterior chamber, and crystalline lens, there is a great variety of devices with the capability of analyzing different anatomical parameters with very high precision. To date, Scheimpflug photography-based systems are the devices providing the more complete analysis of the anterior segment in a non-invasive way. More developments are required in anterior segment imaging technologies in order to improve the analysis of the crystalline lens structure as well as the ocular structures behind the iris in a non-invasive way when the pupil is not dilated.

Keywords: Corneal topography, optical coherence tomography, orbscan, scheimpflug photography, ultrasonography

INTRODUCTION

The anatomical and geometric characterizations of the corneal structure and anterior segment have become a crucial analysis in the clinical practice of ophthalmology for anterior segment specialists. Due to the multiple applications of the analysis of the corneal and anterior segment structures in ophthalmology and their relevance for optimizing corneal and intraocular refractive surgery procedures, different imaging techniques have been developed rapidly in the last few years, mainly because of recent advances in refractive surgery.¹,² All of these imaging techniques provide a specific type of analysis, with some limitations and advantages over the remaining techniques developed. Specifically, the great majority of imaging devices provide a more or less precise and accurate analysis of a specific anatomical and geometric parameter or parameters, with few instruments attempting to provide an integral analysis and evaluation of the anterior segment, including curvature, asphericity, and thickness analysis of cornea and crystalline lens as well as the measurement of the dimensions of the anterior segment space.

The purpose of the present review is to provide a general overview of the available technologies for the anatomical and geometric characterization of the corneal structure and/or anterior segment, showing the advantages and disadvantages of each of them as well as the scientific evidence of their precision and clinical applicability.

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Correspondence: Dr. David P. Piñero, Oftalmar, Department of Ophthalmology, Medimar International Hospital, Avda. Denia, 78, 03016 Alicante, Spain. E-mail: dpinero@oftalmar.es
CORNEAL TOPOGRAPHY

Corneal topography is a non-invasive imaging technique for mapping the anterior surface of the cornea (Figure 1) and, in some cases, of the posterior corneal surface. Considering that the cornea is responsible for over two-thirds of the total eye’s refractive power, its shape is of critical importance in determining the quality of the ocular optical system and therefore the quality of vision. Very small changes in corneal shape resulting from surgery or disease can have a dramatic effect on the focus of the retinal image. For this reason, understanding and quantifying the corneal contour has become an essential preoperative measurement for designing surgical intervention in refractive surgery, for assessing the outcomes of keratoplasty, as well as corneal transplantation, or for evaluating the optical performance of the eye. Several technologies for measuring corneal topography have been developed based on different physical basis that used the following concepts for characterizing the corneal geometry:

- **Height or Elevation**: distance of each point of a surface from a reference surface. Fine details of the cornea can be obtained taking the sphere as the reference surface. Once the shape of the corneal surface has been expressed in terms of height, other parameters such as slope, curvature, and power can be calculated from it.
- **Radius of curvature**: the radius of curvature is usually expressed in millimeters and is a way of characterizing the curvature of the anterior surface of the cornea. Corneas with a steep surface slope have a small radius of curvature, while those with a flatter surface slope have a larger radius of curvature.
- **Power**: the power is an optical property expressed in diopters (D) that depends on the shape of the surfaces and the variation of refractive index between both sides of the surface. The keratometric diopter is calculated using the radius of curvature and the standard keratometric index of refraction (SKI = 1.3375), an approximation derived from some assumptions. We can express this relation with the following formula:

\[
P(D) = \frac{SKI - 1}{r} = \frac{337.5}{r(\text{mm})}
\]
This concept is a simplification ignoring the fact that the refracting surface is air-tear interface, and it does not account for the oblique incidence of incoming light in the corneal periphery. As a result, it miscalculates a true corneal refractive index of 1.376 to 1.3375 to correct for some of these factors. That is why these diopters more correctly are termed keratometric diopters to distinguish them from the diopters expressing more precisely the true refractive power at a certain corneal point.

The evolution of the quantitative assessment of the anterior corneal curvature has been progressive and its range of measurement has been extended from four points a few millimeters apart measured by keratometers to a grid of thousands of points covering almost the entire cornea, measured by computerized corneal topography.

Keratometer

The keratometer uses the ability of the anterior corneal surface to behave as a convex mirror. The Helmholtz keratometer projects four points onto the cornea, creating a reflected image, which can be analyzed and converted to corneal radius data using an equation that considers distance from mire to cornea, image, and mire size. Although keratometers are still used commonly in clinical practice, they have important limitations:

- They perform measurements of the central 3 mm, accounting only for 6% of the corneal surface.
- They assume that the cornea has a perfect spherocylindrical shape, which is not true.
- Information from the periphery is not provided.
- They give no information about the central zone inside the four points measured.

Placido-Based Systems

The patient is positioned sitting down and facing a bowl containing the projected pattern, which is focused on the anterior surface of the patient’s cornea. The pattern reflected off from the cornea is analyzed by a computer that provides data about the geometric configuration of the cornea in different kinds of numerical and graphical formats (Figure 2).

Some of the errors that examiners can make using a Placido-based system are the following: focusing errors, alignment and fixation errors (that could induce wrong levels of astigmatisms), wrong calculation of the position of the center from the small central rings, and increased inaccuracy toward the periphery due to the lack of accuracy of the preceding points.

We can conclude that critical points for a precise measurement are accurate alignment, centering and focusing. These issues depend on the ability of the examiner to take a good measurement. It is essential for obtaining a good exam that the tear film forms a smooth layer over the irregular corneal epithelium. Tear film break-up causes mistracking of the mires and artifacts in the corneal map that appear as irregularity areas or false irregular astigmatism. For example, a dry patch could be associated with an area of focal flattening in the corneal map. In order to avoid disturbing the tear film, corneal topography should be performed before giving dilating drops and taking intraocular pressures.

In spite of being the most widely used, the Placido-based systems present some limitations. The central circle is dark and therefore no real information from this central area is obtained.

- They are designed to capture information along meridians radially, not providing direct information of the corneal geometry circumferentially.
- Approximations based on specific algorithms are used which are not very appropriate when highly irregular corneas are analyzed. Specifically, errors greater than 4D may occur in very steep or flat corneas, keratoconus with local steepening, sharp transition zones after uncomplicated refractive surgeries, diffusely irregular surfaces after penetrating keratoplasty, and complex surfaces after decentered ablations in refractive surgery or central islands.

Scanning-Slit Systems

In the slit-scan systems, a slit is projected sequentially onto the cornea at different angles. This is the basis used by the Orbscan II corneal topography system from Bausch & Lomb (Figure 3). A high-resolution video camera captures 40 light slits projected onto the cornea. The diffuse reflection is obtained from the...
cornea, iris, and lens. By triangulation, data is obtained from the anterior and posterior surfaces of the cornea and from other structures. These issues permit this instrument to calculate anterior chamber depth or full pachymetry of the cornea.\textsuperscript{15} In addition, this device provides data of the elevation and curvature of the posterior corneal surface.

The measurement with this device is significantly dependent on many factors, such as movement of the patient’s eye, stability of tear film, ability of patients to keep the eyes wide open, corneal transparency, and the presence of corneal abnormalities. One of the main limitations of this scanning-slit system is the longer time of image acquisition in comparison with any of the other commercially available instruments. In addition, there are some controversies about the validity of some measurements of the posterior corneal surface provided by the Orbscan system, especially after some types of keratorefractive surgical procedures.\textsuperscript{15} There are numerous scientific studies showing the poor reliability of some measurements of the posterior corneal surface provided by the Orbscan system\textsuperscript{15–19} and articles reporting the error of underestimation of the corneal pachymetry after laser-assisted in-situ keratomileusis, which is assumed to be related to inaccurate detection and location of the posterior corneal surface.\textsuperscript{20–25}

**Scheimpflug Photography-Based Systems**

Scheimpflug imaging is based on the Scheimpflug principle, which occurs when a planar subject is not parallel to the image plane. In this scenario, an oblique tangent can be drawn from the image, object, and lens planes, and the point of intersection is the Scheimpflug intersection, where the image is in best focus.\textsuperscript{26} The Pentacam from Oculus is one of the most recognized systems based on this principle. Specifically, this system uses a rotating Scheimpflug camera to obtain 50 Scheimpflug images of the anterior segment in less than two seconds. Each image has 500 true elevation points for a total of 25,000 true elevation points for the surface of the cornea (Figure 4). Advantages of the Pentacam include the following: (1) high resolution analysis of the entire cornea, including the center of the cornea; (2) ability to measure corneas with accuracy with severe irregularities, such as keratoconus, which may not be amenable to Placido imaging; and (3) ability to calculate pachymetry from limbus to limbus.

The Pentacam system allows the study of both the anterior and posterior corneal surfaces and provides more repeatable and reproducible anterior and posterior measurements (Figure 5) of corneal power than scanning-slit technology. Kawamorita et al.\textsuperscript{27} reported 0.19 of agreement for within-rater consecutive measurements of posterior corneal power measurements of diopter (D) with a Scheimpflug-based system and 0.96 D with a scanning-slit system and for between-rater measurements, of 0.56 D and 1.58 D, respectively.

Other systems based on Scheimpflug photography have been developed and released commercially, such as the Sirius or Galilei systems. The Sirius system (CSO, Florence, Italy) is a topography device which uses the principles of Scheimpflug photography and enables the acquisition and processing of 25 radial sections of the cornea and anterior chamber in very few seconds. The combination between two monochromatic 360°-rotating Scheimpflug cameras and a Placido disk allows a full analysis of the cornea and anterior segment, providing tangential and axial curvature data of anterior and posterior corneal surfaces, and the global refractive power of the cornea, as well as a biometric estimation of various structures, and a corneal wavefront map with an analysis of visual quality and corneal pachymetry maps. Specifically, this system allows a measurement of 35,632 points for the anterior corneal surface and 30,000 for the posterior corneal surface on high-resolution mode in 1–2 seconds.\textsuperscript{28} This device has been shown to provide in normal and even in keratoconus eyes consistent measurements of anterior
and posterior corneal curvature, pachymetry, and anterior chamber depth. Agreement analyses that have been performed to this date suggest that Sirius and Pentacam should not be used interchangeably. The Galilei Dual Scheimpflug Analyzer from Ziemer is a high-precision optical system for corneal topography and three-dimensional analysis of the anterior eye segment based on a revolving dual-channel Scheimpflug camera and a Placido disk. This device combines the advantages of two technologies: Placido imaging furnishes high-accuracy curvature data and Scheimpflug imaging is responsible for capturing precise elevation data. Like the Sirius and the Pentacam systems, the Galilei provides repeatable measurements of corneal curvature and of other anterior segment anatomical parameters. However, the agreement in the measurements obtained with these three Scheimpflug photography-based devices is questionable. The main inconvenience of all these systems based on the use of a rotating Scheimpflug camera is the period of time required to make the complete rotation and therefore to complete the acquisition of the data. This makes the measurements susceptible to tear film stability during such a period.

**ANTERIOR SEGMENT ANALYSIS**

**Scanning-Slit Systems**

The Orbscan II corneal topography system from Bausch & Lomb, based on this technology, is able to provide a pachymetric analysis as well as analysis of the anterior chamber depth (Figure 6). However, a significant limitation in the reliability of the pachymetric measurements is present with these devices, especially in those corneas with their transparency affected and therefore with an inherent complication in the detection of the posterior corneal surface. Anterior chamber depth measurements with the Orbscan system have been shown to be repeatable and in agreement with those obtained with the Pentacam system.

**Scheimpflug Photography-Based Systems**

These systems allow a comprehensive analysis of the anatomy of the anterior segment, including the following analyses: topographic pachymetry (Figure 7), anterior chamber depth, corneal volume, anterior segment diameter (angle-to-angle distance), and crystalline lens densitometry. Several studies have confirmed and validated the consistency of all these measurements. However, these systems, in spite of obtaining an image of the crystalline lens (Figure 8), do not provide an analysis of the curvature of the anterior and posterior surfaces of the crystalline lens. This data would be crucial for some calculations for optimizing a great variety of refractive surgery techniques.

**Optical Coherence Tomography**

Optical coherence tomography is an optical method of cross-sectional scanning based on reflection and scattering of light from the structures within the cornea. Measuring different reflectivity from structures...
within the cornea by a method of optical interferometry produces the cross-section image of the cornea and other anterior segment structures. In optical interferometry, the light source is split into the reference and measurement beams. The measurement beam is reflected from ocular structures and interacts with the reference light reflected from the reference mirror, a phenomenon called interference. The coherent or positive interference characterized by an increased resulting signal is measured by the interferometer and, subsequently, the position of the reflecting structure of the eye can be determined. In this way, the structures of the anterior segment can be visualized with a high degree of resolution (currently 18 microns axial and 60 microns transverse) (Figure 9). This allows imaging of fine structures such as LASIK flaps, Schlemm canal, and lenticles from lamellar keratoplasty surgery to be easily obtained.

The systems based on this technology have the following two main advantages: the measuring procedure is fast and easy for the examiner and patient, and no corneal touch or specific interphase is needed for measuring. They provide a more comfortable procedure of measurement for the patient. All anterior segment structures in front of the iris and posterior segment structures visible through the pupillary aperture can be analyzed precisely with this technology. Several applications have been described for these devices, including analysis of corneal pathology, corneal refractive surgery changes, the position of phakic intraocular lenses (Figure 10), the configuration of the iridocorneal angle area, and changes in the central part of the lens during accommodation. However, AS-OCT has an important limitation: it cannot detect structures behind the iris. Therefore, it is not possible to estimate the sulcus-to-sulcus distance or to analyze the areas of the crystalline lens not visible through the iris. In addition, the device cannot analyze any object behind any opaque structure. It should also be mentioned that this type of device does not provide measurements of the corneal curvature, only an anatomical analysis of the anterior segment.

**Very High-Frequency Ultrasonography**

Ultrasonic systems allow visualization of anterior segment structures, even in the presence of optical opacities. In general, the resolution and depth of penetration are affected by transducer frequency. The traditional ultrasonography of the whole eye uses a...
10 MHz transducer with approximately 150 μm resolution. Higher frequency of a 50 MHz transducer increases the tissue resolution to 50 μm but only at the expense of decreasing tissue penetration depth of 4–5 mm, sufficient to image the anterior segment (Figure 11). Scanning of the cornea is possible with a 100 MHz transducer that increases the tissue resolution to less than 20 μm.

Different applications have been described for this ophthalmic technology; these include intraocular tumours analysis, 44 determination of the position of a phakic intraocular lens, 45 planning for refractive surgery retreatment, 46 micokeratome cut analysis in LASIK, 47 study of intraocular pathology, 48 and

![Figure 7](image-url) Comprehensive pachymetric analysis provided by the Scheimpflug-photography-based system Pentacam.

![Figure 8](image-url) Crystalline analysis by Scheimpflug imaging in a case of posterior lenticus.

![Figure 9](image-url) Image of the anterior segment obtained with the Visante OCT system (Zeiss). © 2013 Informa Healthcare USA, Inc.
analysis of some posterior segment structures.\textsuperscript{49} As resolution normally improves with frequency, VHF waves are used for most anterior segment imaging, providing an axial resolution of less than \(40\mu\text{m}\).\textsuperscript{50} A main advantage of this technology is its accuracy and repeatability.\textsuperscript{51} The problems arise from the measuring procedure. Most ultrasound imaging devices require physical contact between the cornea and the probe, which can be uncomfortable for some patients. As example, the Artemis 2 system (ArcScan) ultrasound device does not require cornea–probe contact; rather, an interface eye transducer of saline is used as the acoustic coupling medium between the cornea and probe. However, the position of the head is uncomfortable for patients and the procedure requires a very experienced examiner. It should also be mentioned that this type of device does not provide measurements of the corneal curvature, only an anatomical analysis of the anterior segment.

**CONCLUSIONS**

The analysis of the anterior segment is a very useful procedure, especially in the field of refractive surgery, allowing a better planning of the surgery, a more comprehensive follow-up, and a better understanding of some postoperative complications. In summary, there are a few main clinical applications of the anterior segment imaging technology:

- Corneal curvature and pachymetric analysis to evaluate the possibility of performing with safety keratorefractive surgery with excimer laser in a specific case.
- Detection of ectatic corneal conditions, especially in the most incipient stages, in order to avoid the performance of laser refractive surgery in such cases and to analyze and prevent the progression of this type of corneal disease.
- Accurate planning of enhancements or retreatments of corneal refractive surgery procedures.
- Analysis of the anatomical outcomes of the different techniques of corneal transplantation.
- Anatomical study of the anterior segment to perform a precise and accurate planning of the implantation of phakic intraocular lenses for the correction of moderate to high ametropia.
- In-vivo evaluation of the real position of an anterior and even posterior segment phakic intraocular lens and the interaction with the adjacent ocular structures.
- Densitometric analysis of the crystalline lens to control and evaluate its transparency and the need for cataract surgery.
- Precise control and monitoring of corneal and anterior segment pathological conditions.
- Analysis of the iridocorneal angle configuration in glaucoma patients.

There is a great variety of technologies available allowing the clinician to perform a characterization of different anterior segment structures. Each technology has different features and is useful for a specific task in the analysis of the anterior segment and cornea. From the Placido-based systems that allow only a characterization of the geometry of the anterior corneal surface to the Scheimpflug photography-based systems that provide a characterization of the cornea, anterior chamber, and crystalline lens, there is a variety of devices with the capability of analyzing different anatomical parameters with very high precision. It is important to know the capabilities and limitations of each technology for performing an optimized use of it. Scheimpflug photography-based systems are to date the devices providing the more complete analysis of the anterior segment in a non-invasive way, allowing the characterization of the
Corneal Structure and Anterior Segment

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