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REVIEW

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Corneal Topography – a Review of Available Investigation Methods and Impact in the Diagnosis and Follow-Up of Keratoconus

Maria-Silvia DINA[a], Maria-Cristina MARINESCU[a], Catalina-Gabriela CORBU[b], Mihaela-Monica CONSTANTIN[b], Catalina-Ioana TATARU[c], Calin-Petru TATARU[c]

[a]Doctoral School, "Carol Davila" University of Medicine and Pharmacy, 020021 Bucharest, Romania

[b]Oftaclinic Ophthalmology Clinic, Bucharest, Romania

[c]Ophthalmology Department, "Carol Davila" University of Medicine and Pharmacy, 020021 Bucharest, Romania

ABSTRACT

Keratoconus is a bilateral non-inflammatory ectatic disease of the cornea, with an asymmetrical evolution, that occurs in young people during puberty, progressing during the second and third decades and stabilizing around the age of 40. It is characterised by an insidious and progressive thinning of the cornea, myopia and astigmatism, which lead to a decrease in visual acuity. Slit-lamp examination findings in the early stages of keratoconus may appear normal. However, in advanced stages of untreated keratoconus, visual acuity is diminished, which leads to a lower quality of life. Corneal topography is essential in the early diagnosis of the disease, analyzing the corneal geometry and thus helping to establish the method of treatment and to follow patients' evolution. This investigation combines the projection of a light source and a video capture system of corneal images with computer processing, providing maps of the distribution of dioptric power over the entire surface of the cornea. Topography can be classified into measuring the anterior surface of the cornea (keratometry and reflection-based topography) as well as both the anterior and posterior surfaces of the cornea (Scheimpflug slit-lamp scanning and pinhole optics). Understanding and reading corneal topographies is essential in correctly diagnosing and staging a keratoconus case. The present review constitutes a comprehensive evaluation of available methods and expected typical results and interpretation, in order to support clinicians in better managing this underdiagnosed ectasia affecting young patients.

Keywords: cornea, keratoconus, topography, videokeratoscopy.

Address for correspondence:
Maria-Silvia Dina
Email: maria-silvia.dina@drd.umfcd.ro

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INTRODUCTION

The cornea has the highest refractive power of the human eye, providing about two-thirds of the dioptric power, with approximately 43–44 diopters at the central. The curvature of the cornea plays an essential role in ensuring refraction and, together with the tear film, it provides an adequate anterior surface for clear vision. Keratoconus affects the curvature of the cornea, being the most common corneal ectasia in the young population. Over time, it leads to a progressive thinning and protrusion of the cornea that has a significant impact on patients' vision and quality of life (1).

Keratoconus is a bilateral non-inflammatory ectatic disease of the cornea, with an asymmetrical evolution, that occurs in young people during puberty, progressing during the second and third decades and stabilizing around the age of 40. It is characterised by an insidious and progressive thinning of the cornea, myopia and astigmatism, which lead to a decrease in visual acuity (2). Clinical manifestation may include blurred vision - even when wearing glasses and contact lenses, frequent prescription of glasses, glare at night, light sensitivity, eye rubbing, irregular astigmatism (3).

In the early stages of keratoconus, slit-lamp examination may reveal no abnormalities. As the condition progresses, some characteristic clinical signs, including Fleischer rings, Vogt striations, corneal thinning and protrusion in the central and paracentral area and corneal scarring, can be detected (4).

The diagnosis of keratoconus is suggested by visual acuity, biomicroscopy, refraction and keratometry. In advanced stages of keratoconus, undiagnosed and untreated, visual acuity is diminished, which leads to a lower quality of life (1). Corneal topography is essential in the early diagnosis of the disease, analyzing the corneal geometry and thus helping to establish the method of treatment and to follow patients' evolution (5).

The outer layer of the eye is made up of the cornea and the sclera. The main purpose of this tunic is to protect the structures inside the eye. The cornea is a transparent tissue, having no blood vessels except at its margins. Thus, the cornea, through its transparency, shape and structure, provides an adequate refractive power that allows for the formation of a clear image on the retina (6, 7).

The corneal layers include the epithelium (thick- ness of 40-50 µm), Bowman's layer (8-15 µm), stroma (470-500 µm), Descemet's membrane (10-12 µm) and endothelium (4-6 µm). Recently, an acellular layer in the pre-Descemet's cornea (called Dua's layer) has attracted attention with the development of lamellar surgery and the latest research suggests that it may have a role in the pathogenesis of keratoconus and that it contributes to corneal biomechanics (6, 8).

The shape of the cornea is convex and aspheric. The curvature and the central area (5 mm) of the cornea play the most important roles for refraction. The cornea has a horizontally oval shape, with a vertical diameter of 9-11 mm and a horizontal diameter of 11-12 mm. The center is thin (0.52 mm) compared to the periphery (0.67 mm). The anterior radius of curvature of a healthy cornea is 7.8 mm and the posterior radius approximately 6.5 mm. The refractive index of the cornea is 1.37 (6, 9).

From the apex to the limbus, the cornea can be divided into four geographical zones, which nowadays can be easily differentiated with the help of color videokeratoscopy of the cornea (10): 1) the central area (diameter of four millimeters centrally), located in front of the pupil and responsible for high-definition vision – it is almost spherical and represents the apex of the cornea; 2) the paracentral area (4-8 mm), which has the greatest flattening; 3) the peripheral area (8-11 mm), which is aspherical; and 4) the limbal area.

A healthy cornea has a smooth surface, being covered by the tear film that blurs the fine irregularities. Thus, this anterior transparent surface of the eye acts as a convex mirror. Using a luminous target, such as Placido discs and an optical system, several instruments, including keratometry, keratoscopy, Placido photokeratoscopy and videokeratoscopy, have been developed to measure the reflection of an incident light falling on the surface of the cornea (3, 11).

The study of the corneal curvature began in the early 1600s by Scheiner. Over the years, various devices were developed by researchers such as Kohlrausch and Helmholtz, and in 1881, Javal and Schiotz created the "keratometer". The principle of light reflection is still used today in corneal topography. However, the data provided by simple keratometry is limited, as measurements are limited to the central curvature of the cornea. Therefore, standard keratometry values vary between 40 D and 47 D, which correspond to an area of 2-4 mm from the center of the cornea (12-14).

Although the knowledge of data provided by a standard keratometer is of great use when we want to either calculate the dioptric power of intraocular lenses or fit contact lenses, the evaluation of the paracentral and peripheral cornea is particularly important for ensuring adequate visual acuity. Corneal topography has offered the possibility of knowing the shape and curvature of the entire corneal surface, which has become fundamental in the evaluation of various corneal pathologies, such as keratoconus, and for the pre- and postoperative evaluation of refractive surgery (12).

Principles of topography

Based on the techniques of keratometry and photoscopy, corneal topography combines the projection of a light source and a video capture system of corneal images with computer processing, providing maps of the distribution of dioptric power over the entire surface of the cornea. The most widely used reflective source is the Placido disc, which has also helped to develop other methods of measuring corneal geometry (15).

Corneal curvature and refractive power can be grouped into two categories: those that measure only the anterior surface of the cornea (keratometry and reflection-based topography) and those that measure both the anterior and posterior surfaces of the cornea (Scheimpflug slit-lamp scanning and pinhole optics) (15).

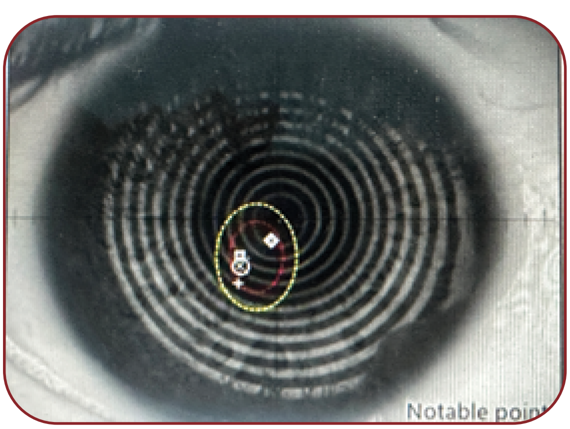

FIGURE 1. Placido disk reflection on the anterior surface of the cornea (personal archive of author M.S.D.)

Depending on the way the images are captured, corneal topographers use the Placido method (Figure 1), Slit scanning technique and Scheimpflug method.

The Placido method involves projecting a series of black and white concentric rings of different sizes on the anterior surface of the cornea. A camera is placed in the center of the rings and thus their reflection is captured from the tear layer that covers the cornea. In this way, the anterior surface of the cornea can be analyzed by the software resulting in the central power of the cornea (3 mm) and SimK values (simulated keratometry). By analyzing the shape of the mires, the system can reproduce not only the central corneal power, but also from any location on the corneal surface. Although Placido-based topography accurately measures the refractive state of the cornea, it cannot reproduce the true shape of the cornea, the posterior surface and the corneal pachymetry (12). Depending on the type of topographer, there are advantages and disadvantages, as described below.

- The corneal topographer based on large-diameter Placido disk rings works at a great distance from the eye and the image obtained can be affected by the conformation of the face, eyelids, eyelashes and shading from the nose. However, this distance from the eye makes these topographers less susceptible to alignment errors between the examiner and the patient, being easier to manipulate.
- The corneal topographer based on small-diameter Placido disk rings works at small distances from the cornea, being more susceptible to alignment errors between the examiner and the patient, but they are not influenced by facial conformation and provide accurate information (5, 16).

Both systems, however, have an important limitation in some cases, especially in corneal ectasias, such as keratoconus where the curvature is very steep (5).

Slit scanning technology is based on the projection of a beam of light onto the corneal surface and the measurement of its projection onto the cornea. Orbscan was originally designed to measure the anterior and posterior curvature of the cornea, as well as corneal thickness. The curvature information was obtained from elevation measurements. Later, a Placido disk attachment was incorporated to obtain curvature measurements directly (12).

Once the Pacido disk rings are projected onto the cornea, 40 slits are projected, 20 to the right and left, at an angle of 45 degrees to the axis of the instrument. The images are recorded by the video camera and evaluated to compensate for eye movements. The data obtained are then processed to provide elevation maps and curvature maps (12).

Scheimpflug technology also uses corneal reflection but the image is captured with a rotating camera. A single rotating camera and a static camera are present in the Pentacam device, which helps 3D visualization of both anterior and posterior corneal surfaces and in calculating pachymetry (12).

It is important to note that, although these systems make similar measurements, the way in which data is acquired and processed is different. Thus, it must be noted that measurements cannot be compared and data are not interchangeable between different types of topographers even if they have the same principle of obtaining images (17).

The main difference between data obtained from a Placido disk system and a Scheimpflug or slit-scan topography system is that the latter two provide information about the posterior cornea. The topographic images provided by Pentacam, which uses Scheimpflug technology, provide precise measurements of the anterior and posterior corneal surfaces, and the system can calculate global pachymetry. Scanning slit topographies, such as the Orbscan, project two vertical scans through 40 optical slits at 45-degree angles to analyze the curvatures of the anterior and posterior corneal surfaces and corneal pachymetry (18).

The numerous advantages over traditional keratometers or keratoscopes like measuring a larger area of the cornea with a much larger number of points and the possibility of storing the images obtained for follow-up, have made corneal topography an extremely important tool in corneal examination. Corneal topography is a non-invasive method that allows a geometric characterization of pathologies that can lead to vision loss: keratoconus, corneal dystrophies, bullous keratopathy, tracking of corneal ulceration or abscess, post-traumatic corneal scars. On the other hand, corneal topography also plays a particularly important role in the preoperative and postoperative evaluation of the refractive patient, penetrating keratoplasty, implantation of corneal intrastromal rings, fitting of contact lenses, evaluation of tear film quality (11, 17).

Image quality is the most important aspect in order to obtain a correct corneal topography. Therefore, it is first necessary for the examiner to take into account the possible situations in which artifacts can be generated, including shadows on the cornea from large eyelashes or trichiasis, ptosis or non-sufficient eye opening, tear film disorders, too small distance between the cornea and the small diameter Placido disc rings and incomplete or distorted image (corneal pathology) (11).

Understanding corneal topography

Color scales

Modern topographers use the Louisiana State University Color-Coded Map which corresponds to the following: 1) blue-purple shades, representing flatter corneal areas (low dioptric power); 2) yellow-green shades, which define normal corneal curvatures; and 3) red-orange shades, that correspond to steep curvatures (high dioptric power) (19).

In the normal cornea, the range of dioptric powers varies depending on the location: 39 D at the periphery, near the limbus, and up to 48 D at the apex of the cornea. The colors match to curvature values and do not always correspond with the elevation map. The nasal cornea is flatter than the temporal, so it becomes blue more quickly (17).

Topographic scales

Two basic scales, absolute and relative, are commonly used, as described below.

Absolute/standard scale – uses fixed color-coding that is the same for all patients and every map produced, allowing for consistent comparison between different exams or different patients. It was designed to make only clinically relevant information obvious, by setting the interval between the contours of the power plot at 1.5 diopters (low resolution) (17, 20).

Relative, normalized or adaptative color scale – color range according to the range of colors present in a given cornea. This method is best suited for assessing variations within an individual cornea. Its primary advantage lies in its high topographic detail, achieved through smaller incremental steps that enhance resolution (19).

However, these small steps also increase sensitivity by introducing more color gradations, which can exaggerate minor or normal variations and create confusion for the examiner to interpret the map, potentially leading to misdiagnosis. On the other hand, using larger steps reduces sensitivity, masking possible significant changes by smoothing the data between measurement rings (17).

User-defined scale – some topographers allow users to define their color scale, thus customizing it to specific needs or preferences (20).

Corneal maps

• *Axial map (sagittal map)* is the most commonly used map that generates measurements using the keratometer formula to evaluate the general characteristics of the cornea and to classify corneal maps (normal or abnormal). It can differentiate spherical from astigmatic or irregular corneas, providing measurements that are easy to interpret even by less experienced users. The disadvantage of this type of map is that it compares the corneal surface to a sphere. It is relatively precise in the examination of the central area of the cornea, but it achieves a marked general smoothing of the periphery of the cornea, this type of map not being suitable to properly examine the peripheral corneal area (5, 11, 17).

• *Tangential map* provides more precise data about the periphery of the cornea, not based on comparing the cornea to a sphere but mathematical formulas of the radius. It is more useful in the diagnosis of keratoconus, localizing conical ectasia and guiding the localised laser ablation in refractive surgery (5, 11).

• *Height map* is very useful to numerically quantify the altitudinal level of a corneal defect such as ulcers or keratoconus (their height or depth). Height data (in micrometers) is readily available from topographers using the projection principle.

• *Refractive map* applies Snell's law to calculate the refractive power of the cornea, using the axial map. It is mainly useful in refractive surgery (5, 11).

• *Elliptical elevation map* compares the anterior and posterior surfaces of the cornea with an elliptical surface, a more appropriate resemblance than the spherical one. As it provides a better visualization of the corneal shape, it can display the height of the corneal surface at different points in micrometers (11).

• *3-D reconstruction map* more realistically reproduces the shape of the cornea.

• *Irregularity map* is used after refractive surgery to detect corneal irregularities that could cause reduced visual acuity. It is based on information obtained from axial maps and tangential maps

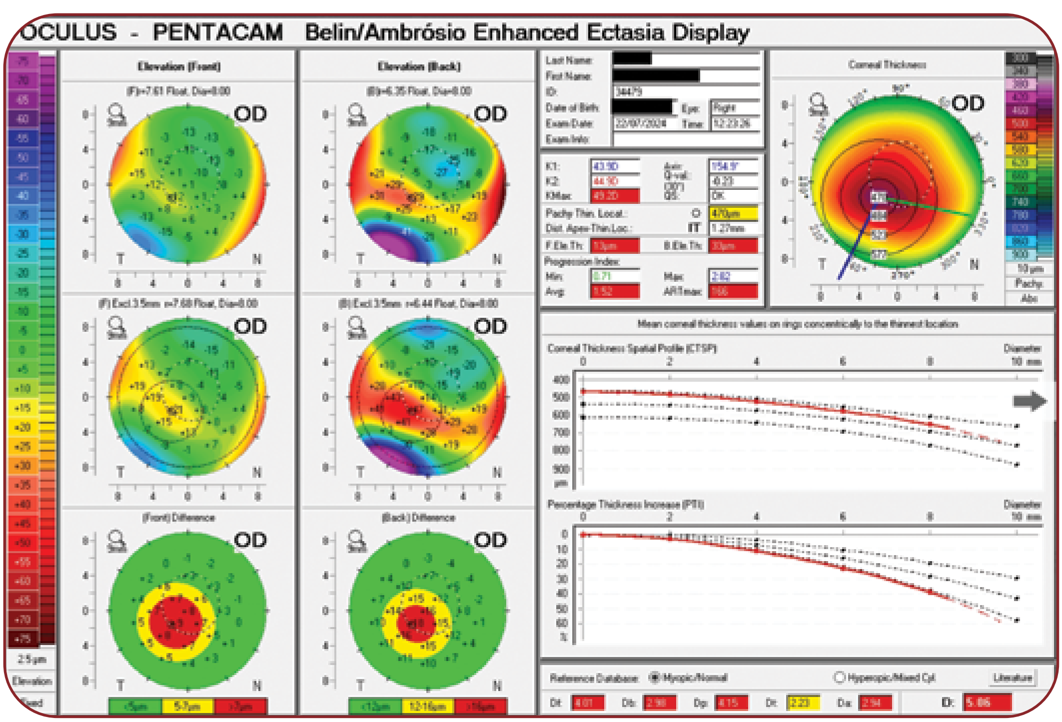

FIGURE 2. Keratoconus stage 1, elevation maps with Pentacam (personal archive of author M.S.D.)

calculating the corneal sphere/cylinder correction (11).

Certain topography devices offer specific maps, including the Slit scanning Orbscan and Scheimpflug-based Pentacam. The typical Orbscan maps are: 1) anterior float – elevation map of the anterior cornea; and 2) posterior float – it is important as Placido based systems cannot pick up early signs of ectasia, which starts from the posterior float;

• *Keratometric map* gives the keratometric values for anterior cornea.

• *Thickness map*.

The typical Pentacam maps (3) include sagittal curvature maps; anterior elevation maps (front) (Figure 2); posterior elevation maps (back) (Figure 2); tangential maps; pachymetry or corneal thickness; and Belin-Ambrosio enhanced ectasia display.

Regardless of the type of topographer, when we look at a corneal topographic map of a healthy eye we can observe: a round appearance; regular astigmatism according to the rule – vertical "bow-tie" oval; regular astigmatism inverse to the rule – horizontal "bow-tie" oval; and oblique astigmatism – diagonal "bow-tie" (21). Irregular astigmatism, in which the "bow-tie" is asymmetrical, can be determined by dry eye, keratoconus, traumatic scars, corneal edema, pterygium, corneal warpage and corneal surgeries (21).

Topographic maps also allow a classification of the severity of the cone:

- subclinical – inferior cone, hourglass-shaped, not detectable biomicroscopically;
- mild clinical – inferior cone, oval, hourglass-shaped, sometimes detectable biomicroscopically;
- moderate clinical – central and/or inferior cone, globular, detectable biomicroscopically (see Figure 3); and
- clinically severe – cone located superiorly, sharp, detectable even without a biomicroscope (19).

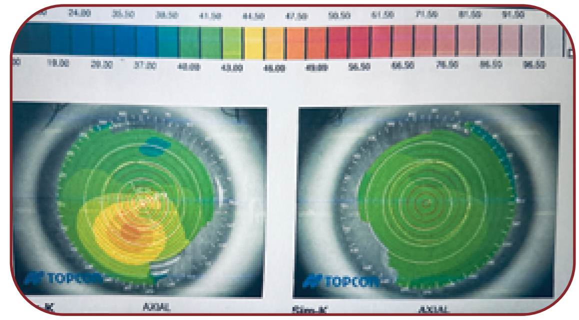

FIGURE 3. Typical topographical aspect of keratoconus in the right eye, with the appearance of the inferotemporal cone of a yellow-orange color indicating the steeper curvature of the cornea compared to the left eye, which appears normal (personal archive of author M.S.D.)

Topographic indices

All topographic and tomographic machines have normal values of the parameters evaluated in the system. Individual indices derived from corneal topography have specific purposes. Corneal topography primarily serves to quantify irregularities in corneal shape through indices that reflect both local and overall deviations in morphology. Generally, more than three abnormal topographic maps, a difference greater than 0.05 diopters between the anterior and posterior surfaces, irregularities at 3 and 5 mm, variations in astigmatism between the two eyes, high corneal diopter values or changes in peripheral thickness are considered risk criteria for ectasia (21).

Considering the importance of this investigation in the diagnosis and follow-up of corneal ectasias, topographers also offer specific indices for keratoconus. In addition, given that early changes are not obvious, several univariate or multivariate indices for detecting keratoconus have been integrated into modern topographers (5).

1. Indices provided by Placido-based topography and their normal values

- K (central K reading): normal values below 47.2 D, above this value is considered suspicious keratoconus;
- ACP (average corneal power): normal values between 40.5 and 46.7 D;
- I-S (inferior-superior asymmetry): normal values below 1.4; values higher than 1.4 raise suspicion of keratoconus;
- CAI (corneal asymmetry index): positive for prolate surface/negative for oblate surface: -0.114 to 0.806;
- SDP (standard deviation of power): normal values between 0.37 and 1.33;
- DSI (differential sector index): normal values between 0.21 and 3.51;
- OSI (opposite sector index): normal values between -0.55 and 2.09;

- CSI (center surround index): normal values between -0.28 and 0.80;
- IAI (irregular astigmatism index): normal values between 0.19 and 0.49;
- SAI (surface asymmetry index): normal values between: 0.10 and 0.42;
- SRI (surface irregularity index): normal values between 0 and 0.56;
- AA (area analyzed): normal values between 0.70 and 0.94 (12).

2. Indices to detect anterior keratoconus with Orbscan IIz™

- Posterior best fit sphere power below 55 D is normal and a value above 55 D raises suspicion of corneal ectasia;
- The ratio of the radius of the best-fitting anterior sphere to the best-fitting posterior sphere: values below or equal to 1.21 are considered normal, while those above 1.22 are suspect for corneal ectasia;
- CTI (corneal thickness index): values below 1.16 are considered normal and those above this threshold are considered suspect for corneal ectasia;
- Differences up to 1.15 D in the 3 mm area are normal and those above 1.15 D are suspect for corneal ectasia;
- Differences below 2.5 D in the 5 mm area are normal, and those above 2.5 D are suspect for corneal ectasia

3. Indices to detect anterior keratoconus with Pentacam (11):

- Index of surface variance (ISV) – A value >37 is yellow and is considered abnormal, while a value > 41 is red and is considered pathological;
- Keratoconus index (KI) – Values >1.07 are abnormal;
- Central keratoconus index (CKI) – Values >1.03 are abnormal;
- Index of height decentration (IHD) – Values >0.014 are abnormal and those >0.016 are considered pathological;
- The minimum radius of curvature (Rmin) – Values <6.71 are abnormal;
- Index of vertical asymmetry (IVA) – Values >0.28 are abnormal and those >0.32 are considered pathological;
- Index of height asymmetry (IHA) – Values >19 μm are abnormal and those >21 µm are considered pathological (12).

4. Multivariate indices for keratoconus

Subclinical keratoconus is easier to diagnose using multivariate combinations of the topographic indices described above.

- 'I-S ratio', which represents the amount of steepening of the inferior cornea compared with that of the superior cornea: a cut-off value of 0.8 D is used to distinguish between normal eye and suspect keratoconus;
- Keratoconus prediction index (KPI) is derived from eight other videokeratography indices, including the ones that suggest the asymmetry of the corneal surface (DSI, OSI, CSI), those related to the degree of corneal toricity (SimK1, SimK2), the irregular astigmatism index and the percent analyzed area. A value greater than 0.23 is suggestive of keratoconus;
- KISA% derived from central K, I-S, the astigmatism index (AST), which quantifies the degree of the regular corneal astigmatism and SRAX index, an expression of irregular astigmatism occurring. Values between 60 to100 indicate a suspicion of keratoconus,

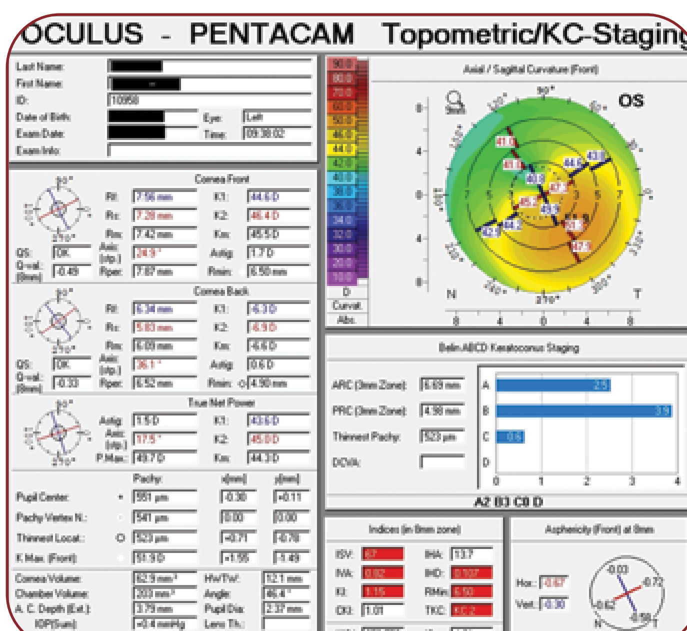

FIGURE 4. Keratoconus stage 2, integrated indices and Belin ABCD keratoconus staging with Pentacam (personal archive of author M.S.D.)

while those higher than 100 are a diagnosis of keratoconus. KISA has a high sensitivity and specificity in the diagnosis of clinical keratoconus (22);

- Keratoconus index (KCI) – This method differentiates between a healthy cornea and a cornea with keratoconus and can detect the location of the cone, distinguishing between keratoconus developed in the central or peripheral corneal regions;
- Keratoconus severity index (KSI) – This multivariate system can differentiate between a healthy cornea and one affected by keratoconus or suspected of keratoconus. Depending on the displayed values, we can determine if the cornea does not have keratoconus (KSI is below 15%), if there is suspicion of keratoconus (KSI varies between 15 and 30%) and in the case of subclinical or clinical keratoconus (KSI above 30%);
- The Belin Ambrósio enhanced ectasia display III (BAD III) (Figure 4) uses nine parameters, including the anterior and posterior elevation at the point of minimum thickness, anterior and posterior elevation change, progression of corneal thickness, the thickness of the cornea at its thinnest point, the location of the thinnest point, Ambrósio relational thickness and Kmax. The BAD III index provides information for each parameter and then performs an analysis of the nine indices, which allows discrimination between healthy and keratoconic corneas (5).

Pentacam offers the Belin ABCD classification for keratoconus staging, surpassing the limits of the Amsler-Krumeich and KSI classifications by being able to measure the thickness of the cornea at the point reported as being the thinnest, as opposed to a central reading, which may be different in KC (23).

CONCLUSION

As many practitioners have noticed, the prevalence of keratoconus seems to be increasing, given that the clinical and paraclinical characteristics are more widely known and certain risk factors – mainly allergies – are more common in the population (24). As such, corneal topography plays an essential role, in screening the potential suspects, diagnosing early cases of keratoconus, following the evolution of this disease and, importantly, guiding the choice and personalisation of treatment. A good knowledge of these imaging methods and the emergence of newer and more precise topographical instruments for the cornea allow for a correct treatment of our patients and a limitation of the disease's impact on their lives.

Corneal topography is the most important examination for early diagnosis of keratoconus, disease assessment and progression monitoring. ❑

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