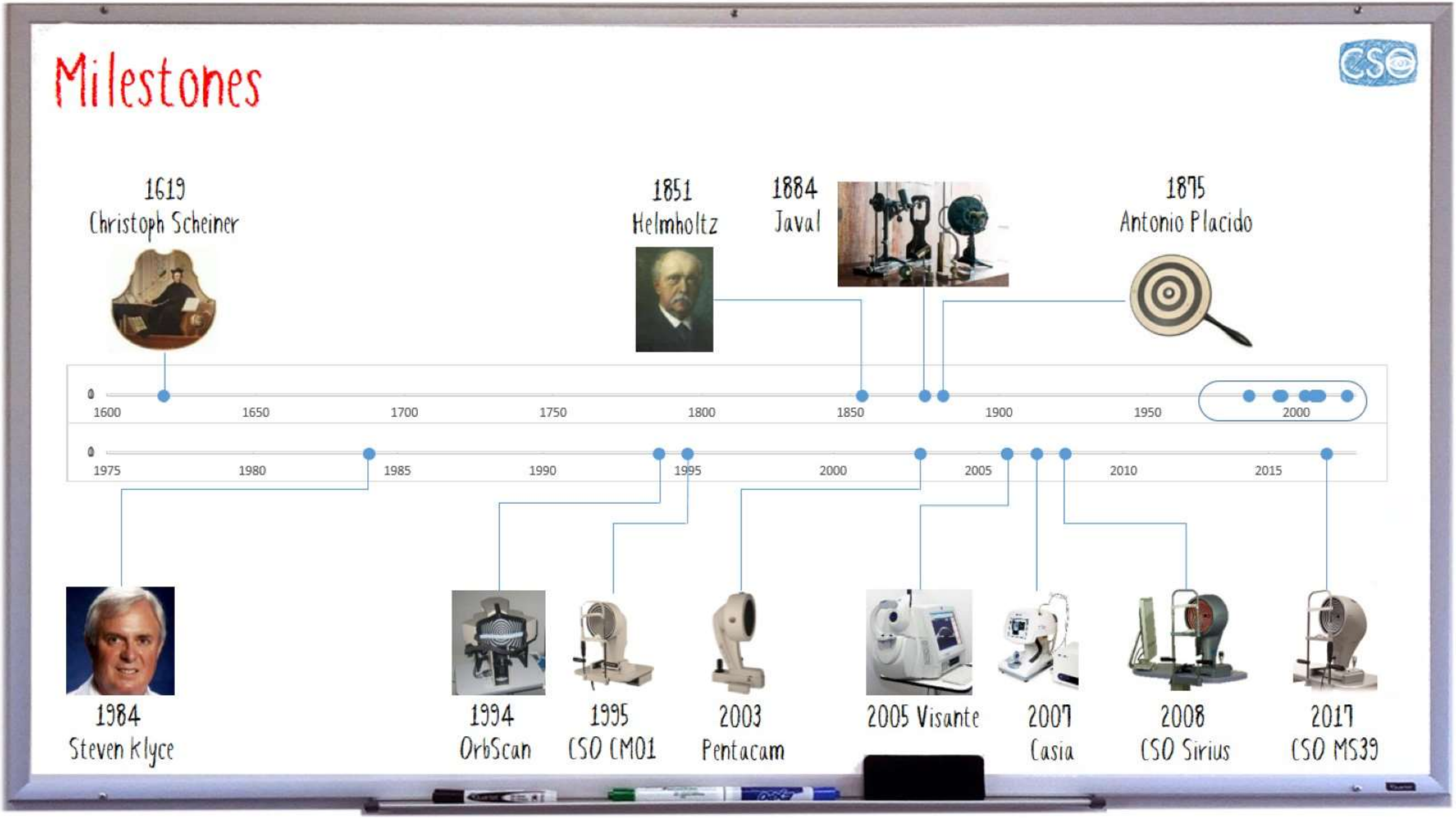
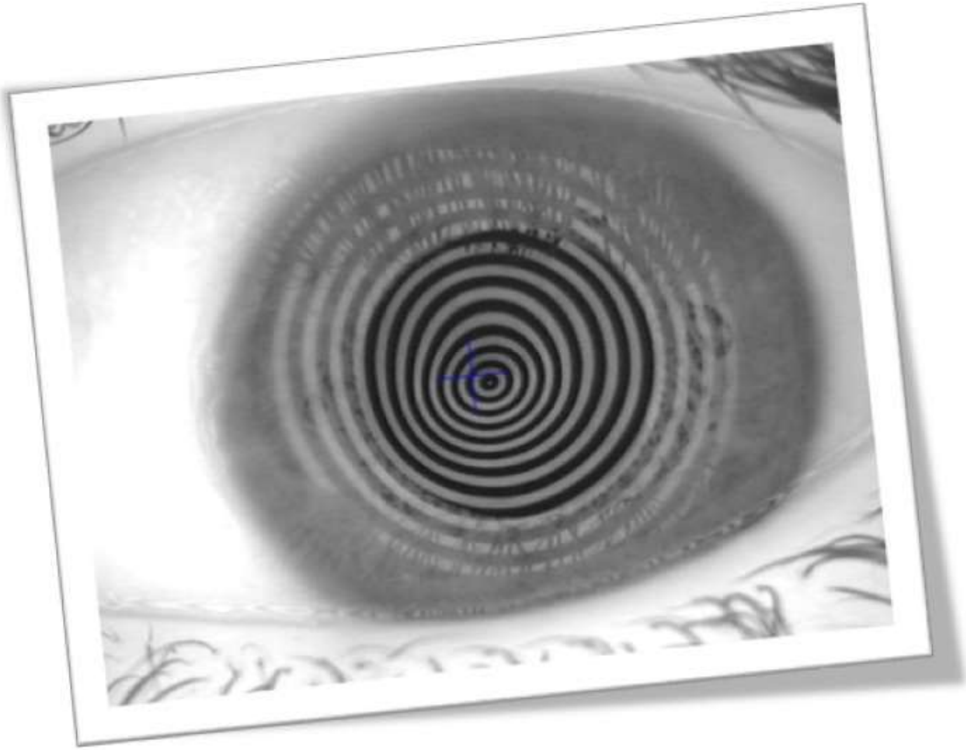
Corneal topography: brief historical notes

Gabriele Vestri

Francesco Versaci

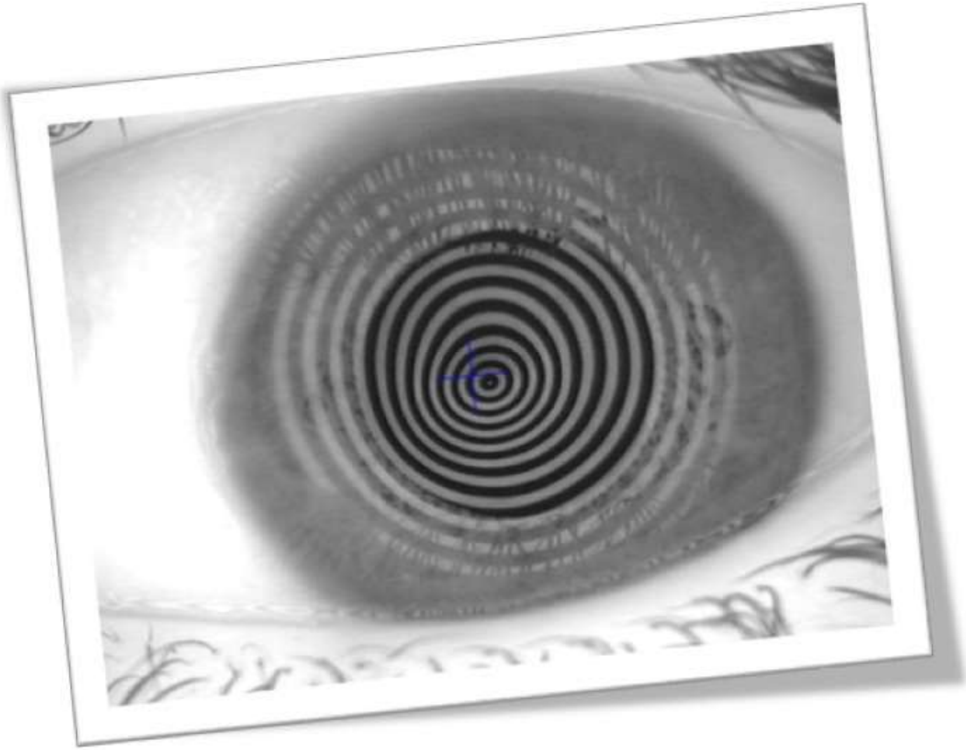

Milestones
1619
Christoph Scheiner
1851
Helmholtz
1884
Javal
1875
Antonio Placido
0
1600
1650
1700
1750
1800
1850
1900
1950
2000
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
1984
Steven Klyce
1994
OrbScan
1995
CSO CM01
2003
Pentacam
2005 Visante
2007
Casia
2008
CSO Sirius
2017
CSO MS39

Placido disk: qualitative evaluation



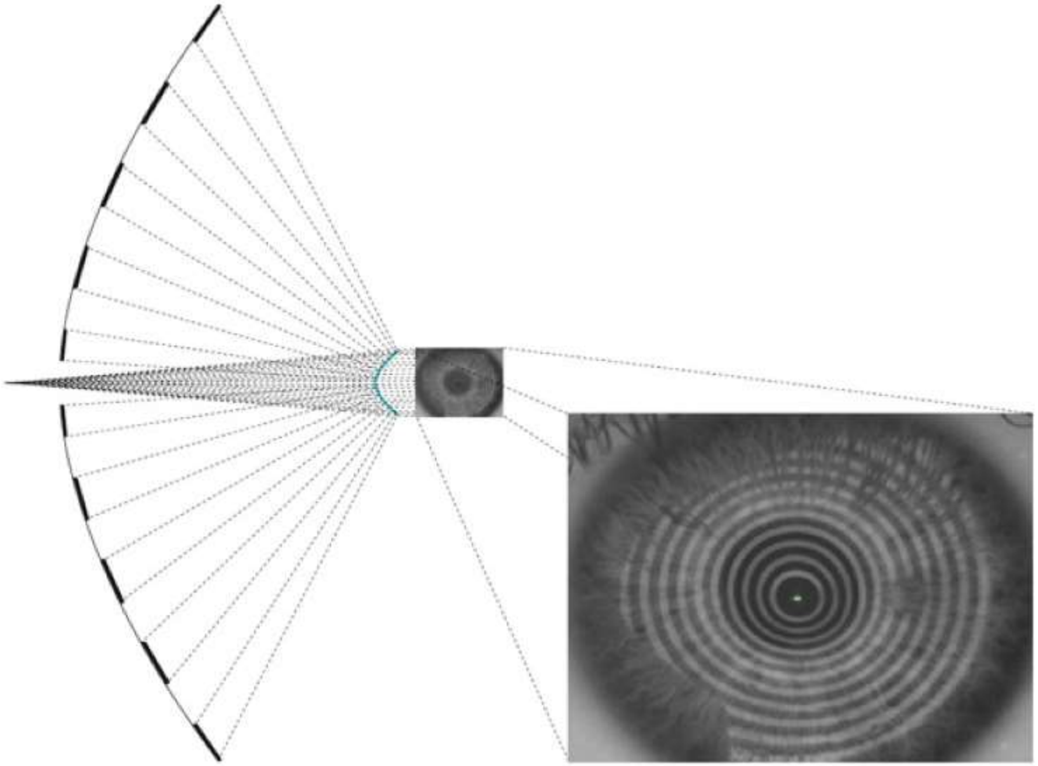
Keratoscopy observation born as a method to evaluate modifications of the corneal curvature by the reflection of a known pattern on the cornea.

Videokeratoscopes: quantitative evaluation



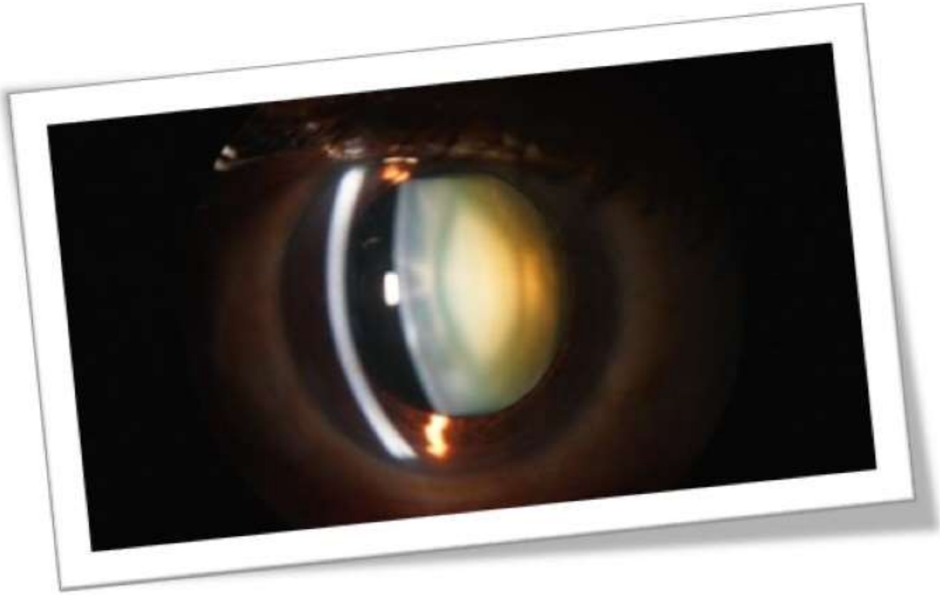
Conceptually, we can consider modern videokeratoscopes as a derivative of keratometers, so much so that the first method developed in this regard is based on the same principles of the keratometer.
A topographic map can be calculated as many keratometries done with mires of various sizes and orientations, centered on the same axis.

Arc-Step algorithm



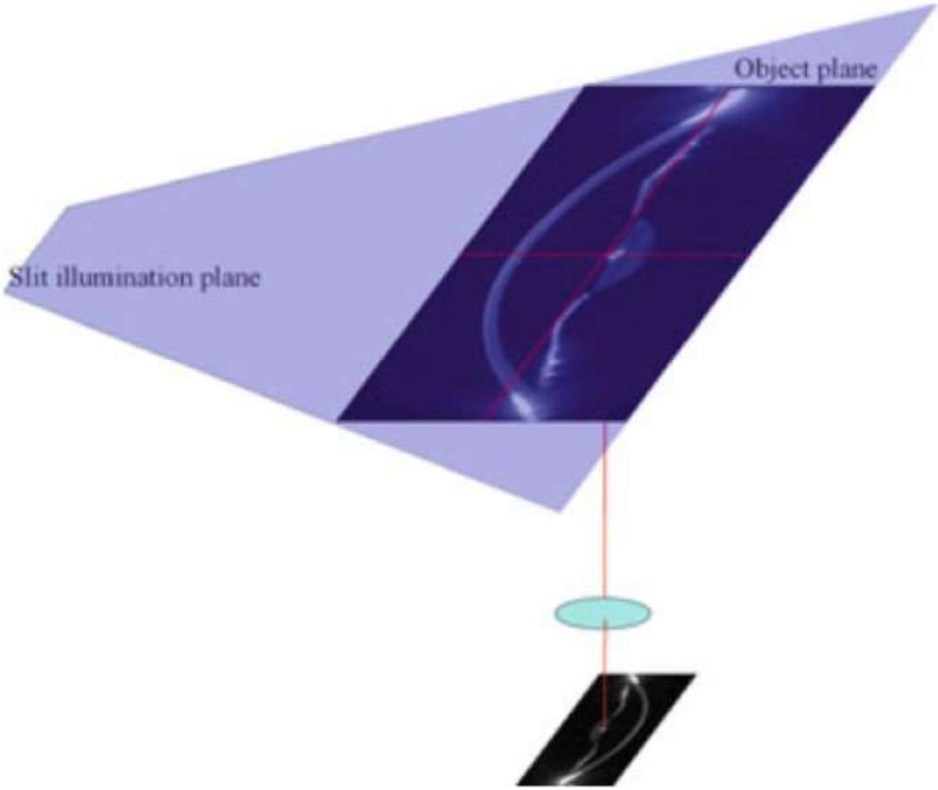
In recent generation reflection-based topographers, normal to the cornea, curvatures and elevations are calculated simultaneously by a process called *arc-step*.

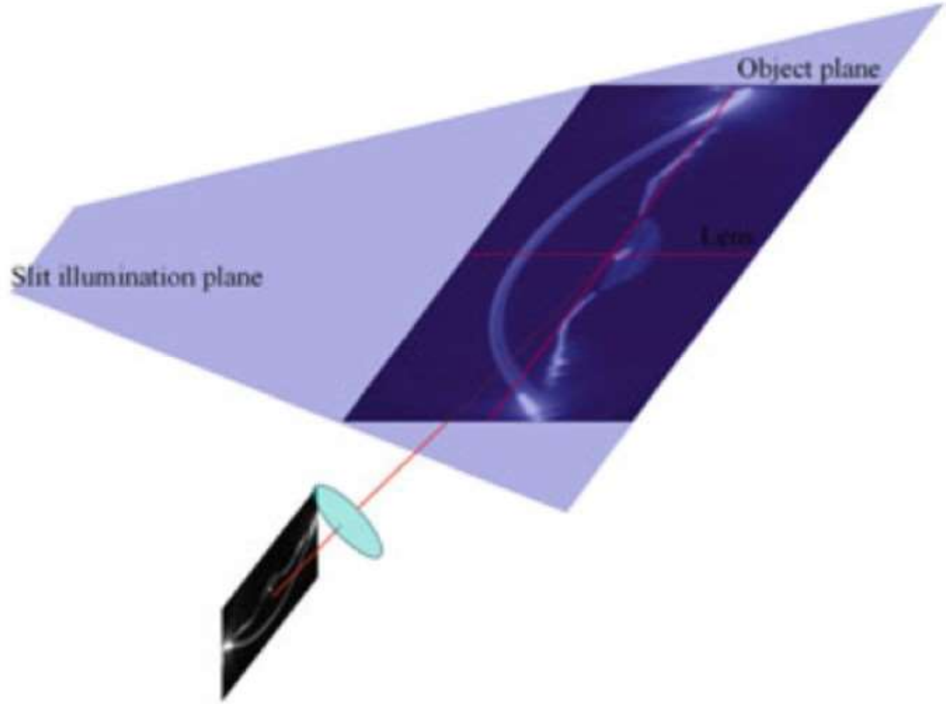
Optical scanning devices



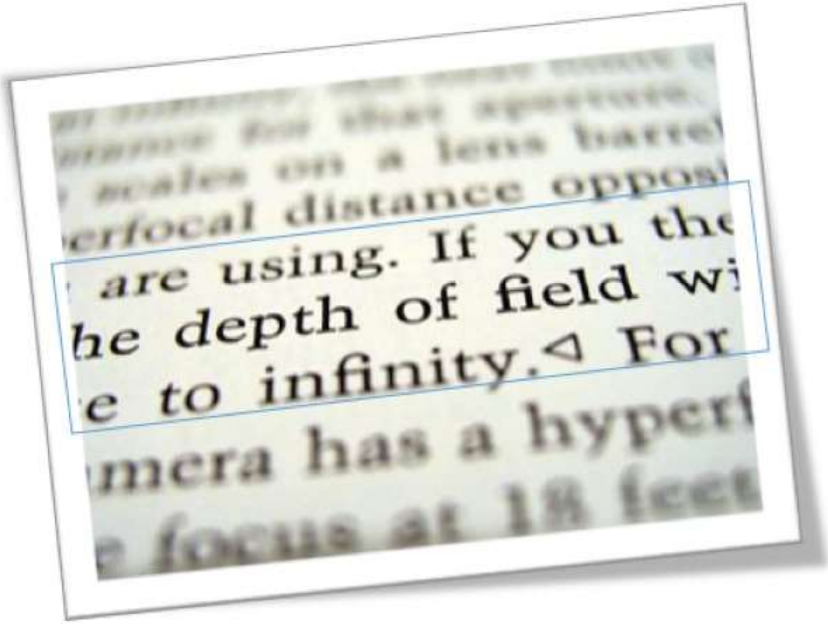
- Directly measure the height of the front surface and the back cornea.
- Usually, the transverse FOV goes from limbus to limbus and the vertical is such as to include the entire anterior chamber.
- Based the projection light slits which, scatter in every direction. Part of the back-diffused light is captured by a suitable optics able to form the image on the CCD.

Scheimpflug cameras





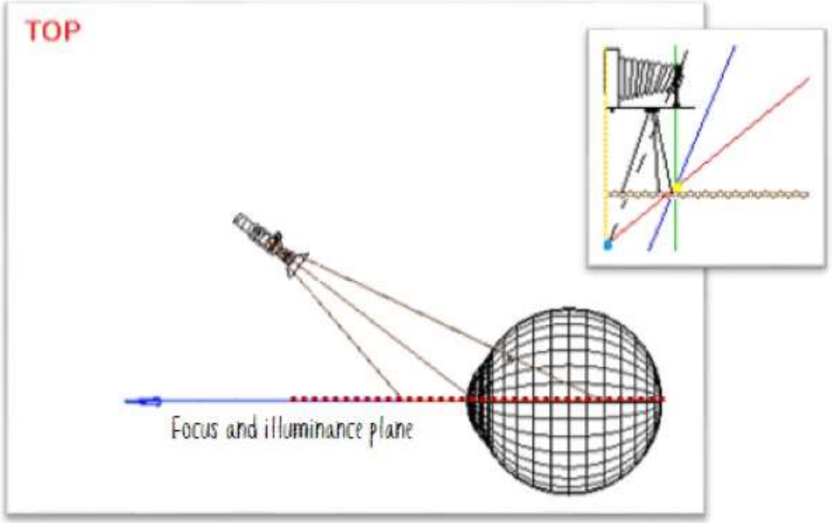
The Scheimpflug principle



With a normal camera, if the subject is not parallel to the image plane, just a little region is in focus.

http://en.wikipedia.org/wiki/Scheimpflug_principle

The Scheimpflug principle

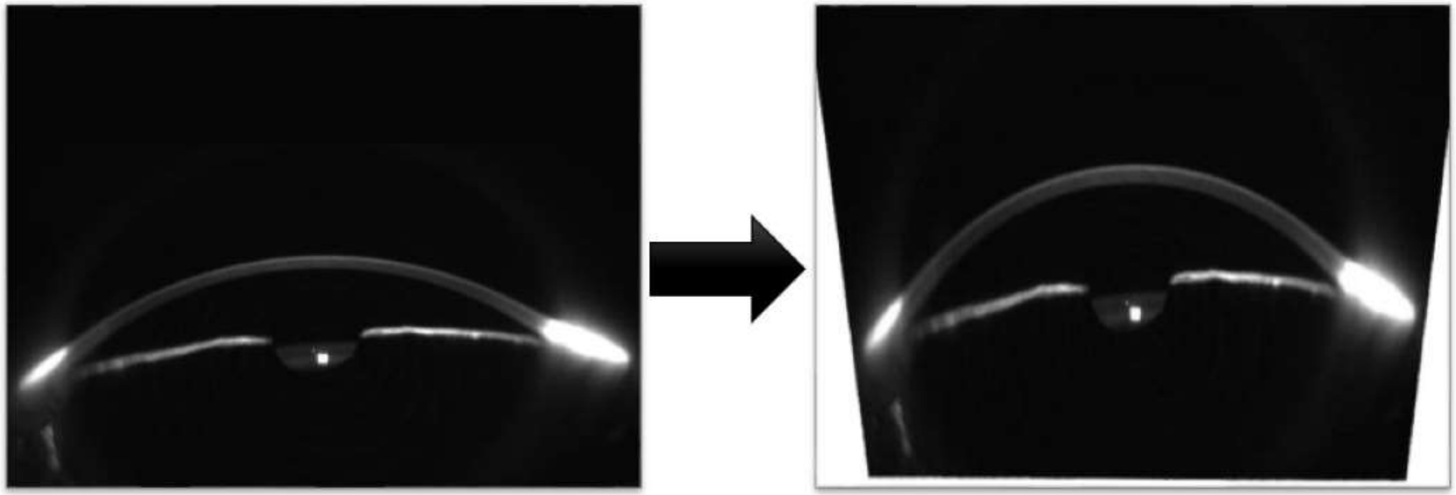


The Scheimpflug principle is a geometric formula describing the orientation of the focus plane of an optical system (e.g. CCD) if the lens plane is not parallel to the image plane.

http://en.wikipedia.org/wiki/Scheimpflug_principle

The Scheimpflug principle

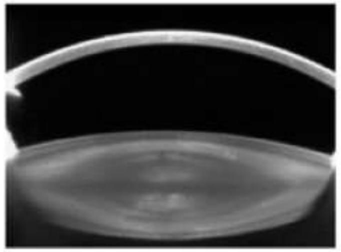
The Scheimpflug setup corrects defocusing, not distortion!!!



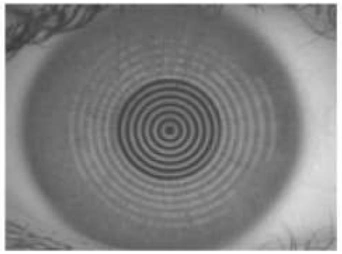
The Scheimpflug principle: the 3rd dimension

Once scanned the first image, the light blade and the Scheimpflug system can be rotated in order to acquire images of a succession of equidistant angular sections that allow to completely map the anterior segment of the eye.

Hybrid devices



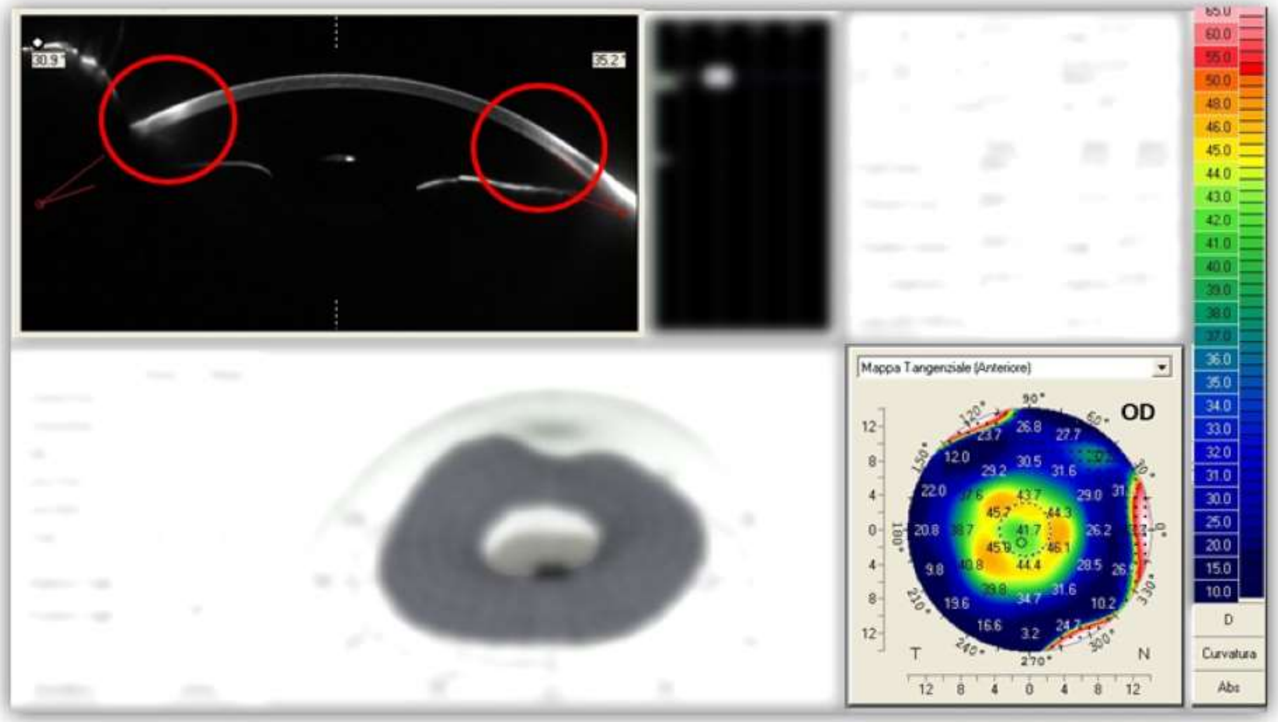
Scheimpflug images give accurate corneal elevation data for the whole anterior segment



Placido disk gives better results on the representation of curvature and refractive powers

Some devices (e.g. Sirius) merge Placido disk data with the Scheimpflug system data. The integration of the two technologies allows to obtain the accurate measurement in elevations, curvature and power terms for the whole cornea

Hybrid devices advantages

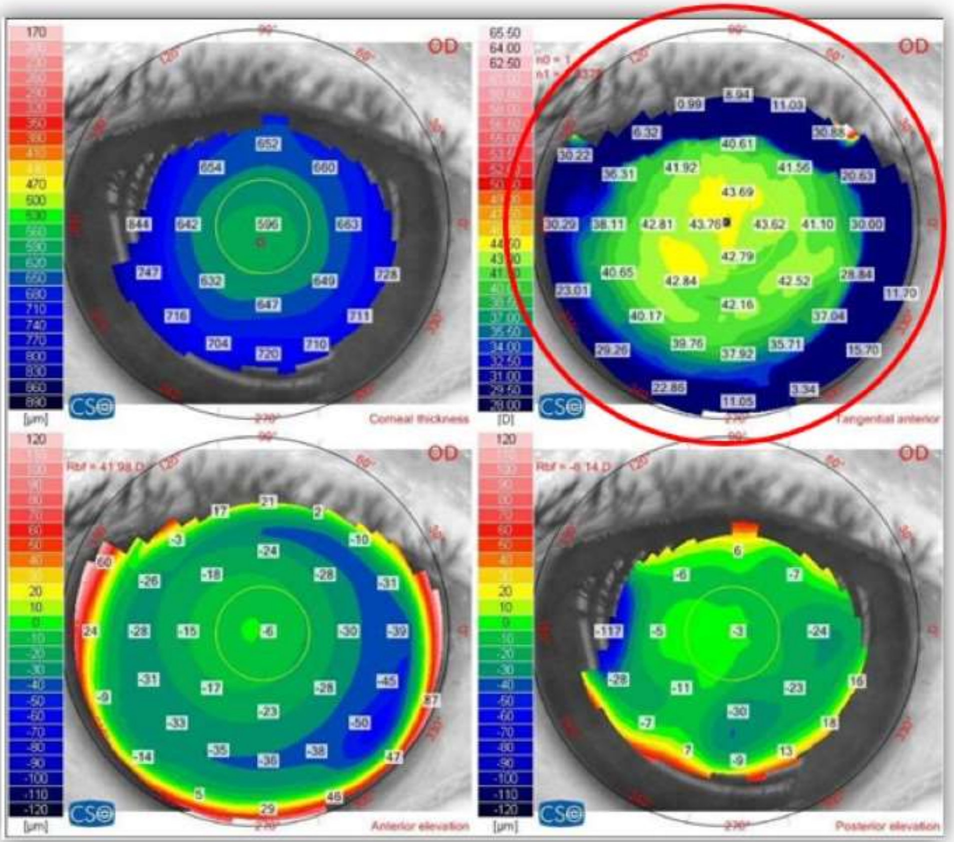


Hybrid devices advantages

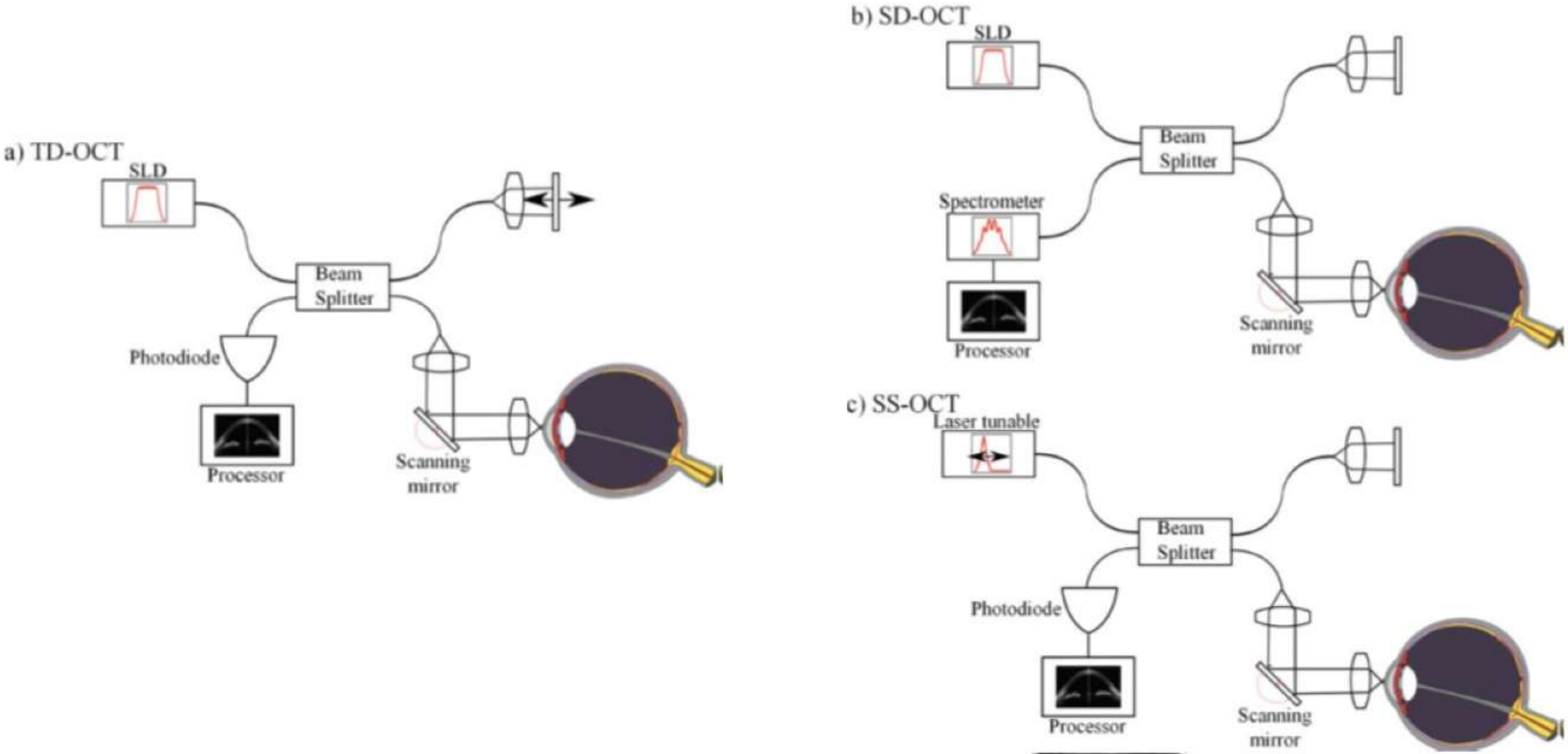
Gerontoxon (Arcus senilis):

A common finding in the elderly but of no pathological significance. It is formed by lipid deposition at the periphery of the cornea. This condition is also found in familial hypercholesterol-anemias.

Hybrid devices advantages



Ultimate generation topographers: Optical coherence tomography



Spectral domain OCT: MS39 specifications

- Light source: SLED @ 849nm BW≈80nm
- Axial resolution (air/tissue): 4.8/3.5μm
- Transverse resolution: 35μm
- Max.Scan Range (air): 16x16x10 [mm]

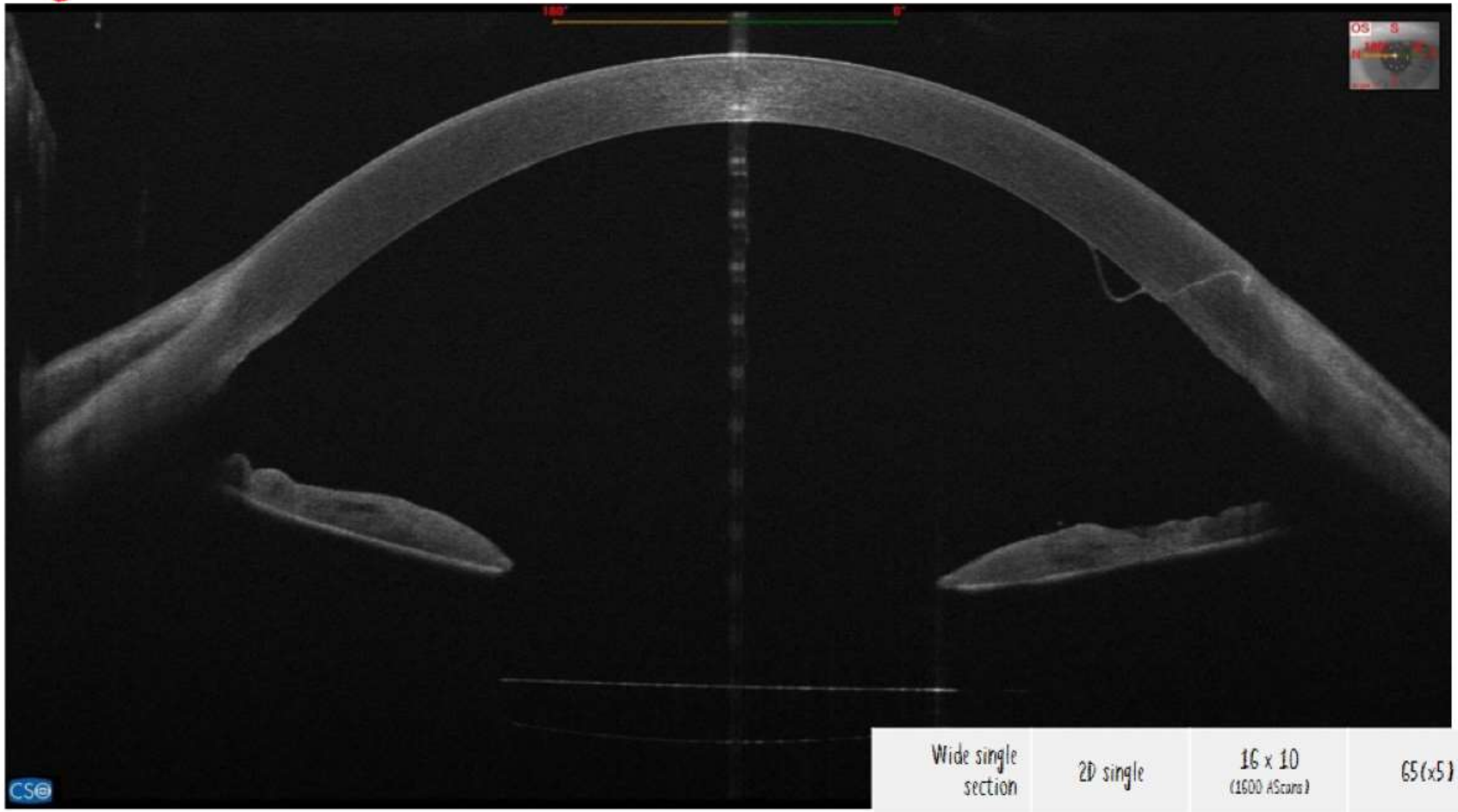
- Placido disk: 22rings @ 635nm
- Keratoscopy size : 14mm x 10.5mm

- Type A according to ISO 19980:2012

Acquisition main modalities

	Scan method	Range (Transverse x Axial in Air) [mm]	Acq.Time [ms]	Img mode
Wide single section	Single line	16 x 10 (1600 AScans)	65(x5)	Raw (Averaged)
10mm single section	Single line	10 x 3.9 (800 AScans)	32(x12)	Raw (Averaged)
Corneal map	Radial scans of 25 sections	16 x 10 (1024 Ascans)	<1000	Raw

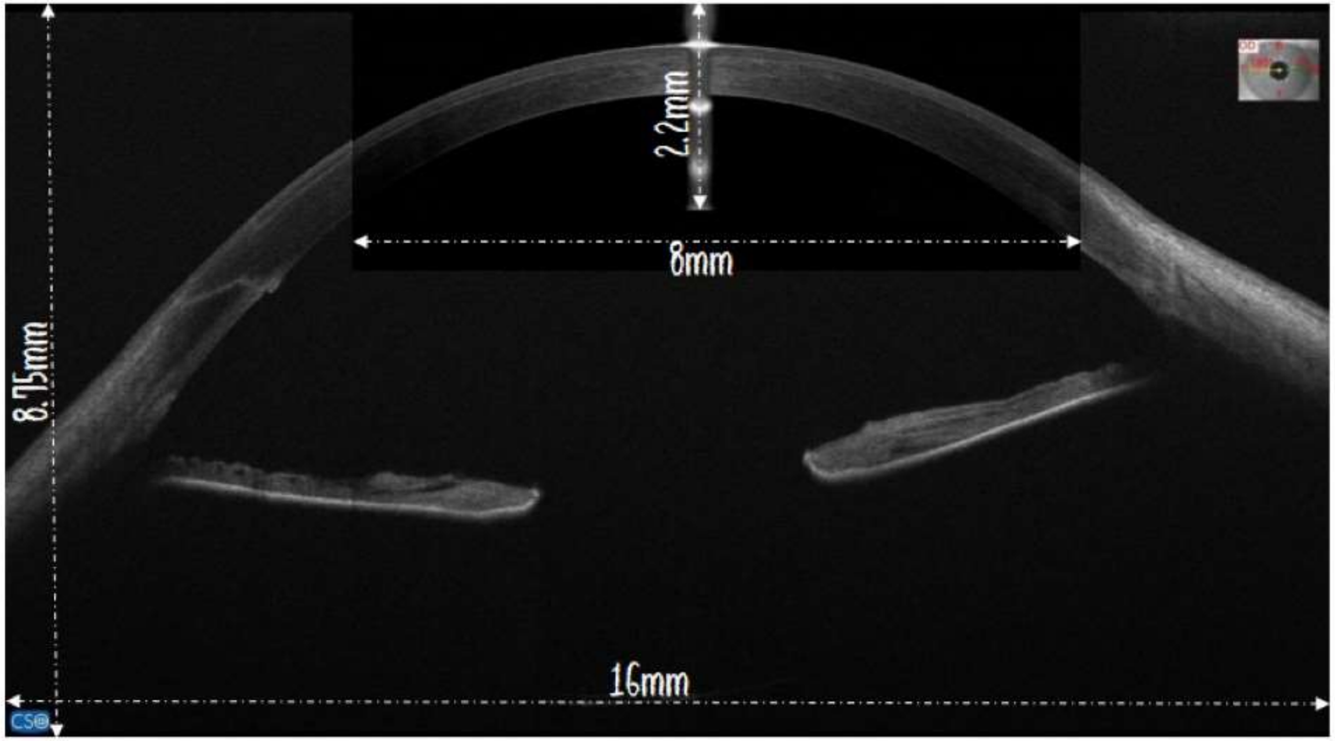
Wide single section



Wide single section	2D single	16 x 10 (1600 AScans)	65(x5)	Raw (Averaged)

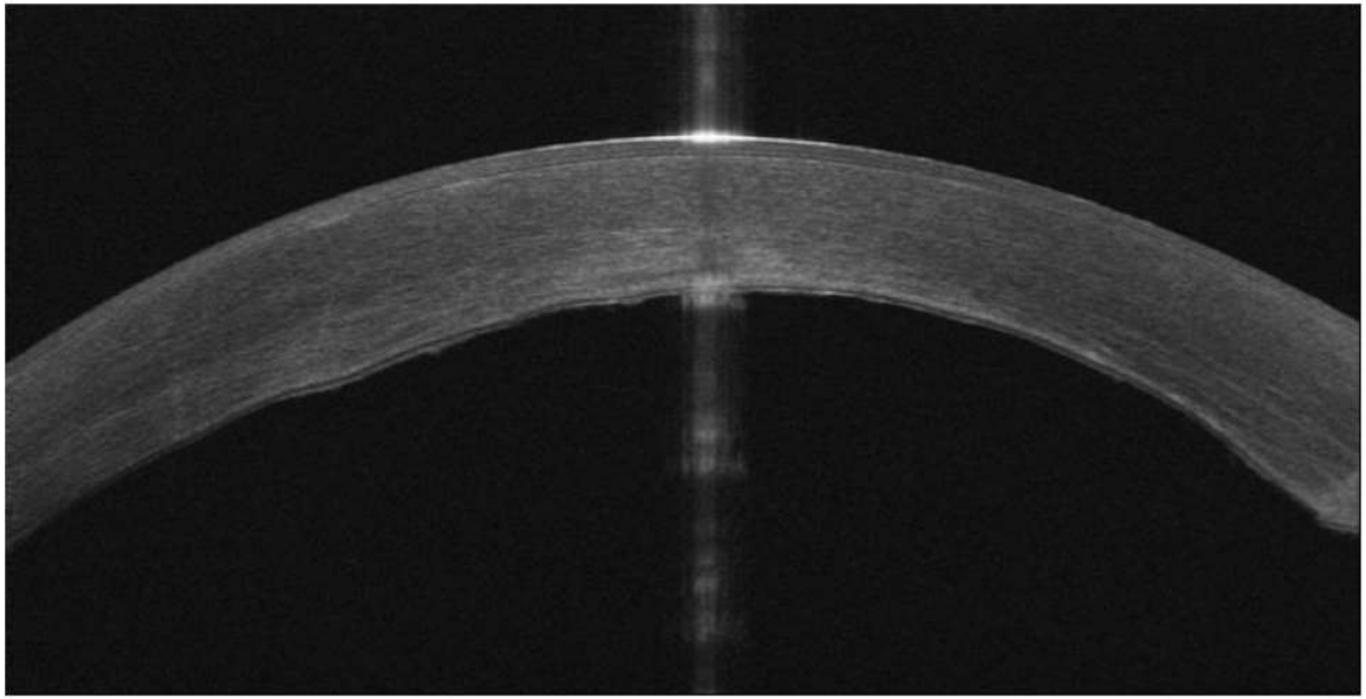
IOL + Endothelial detachment: Courtesy of Dr.Claudio Macaluso

AS-OCT vs. Retinal OCT + Corneal Adaptor Module



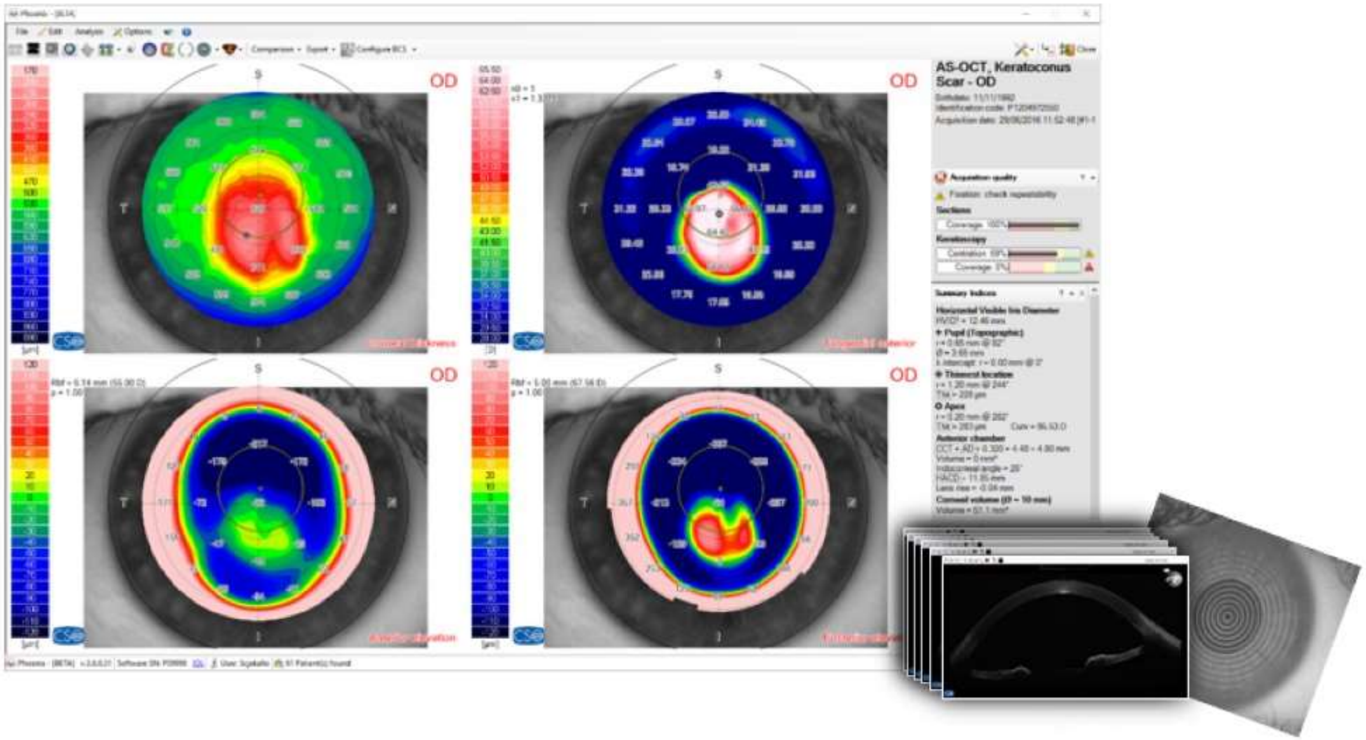
Femtolasik flap: Courtesy of
Dr.Francesco Carones

10mm single section



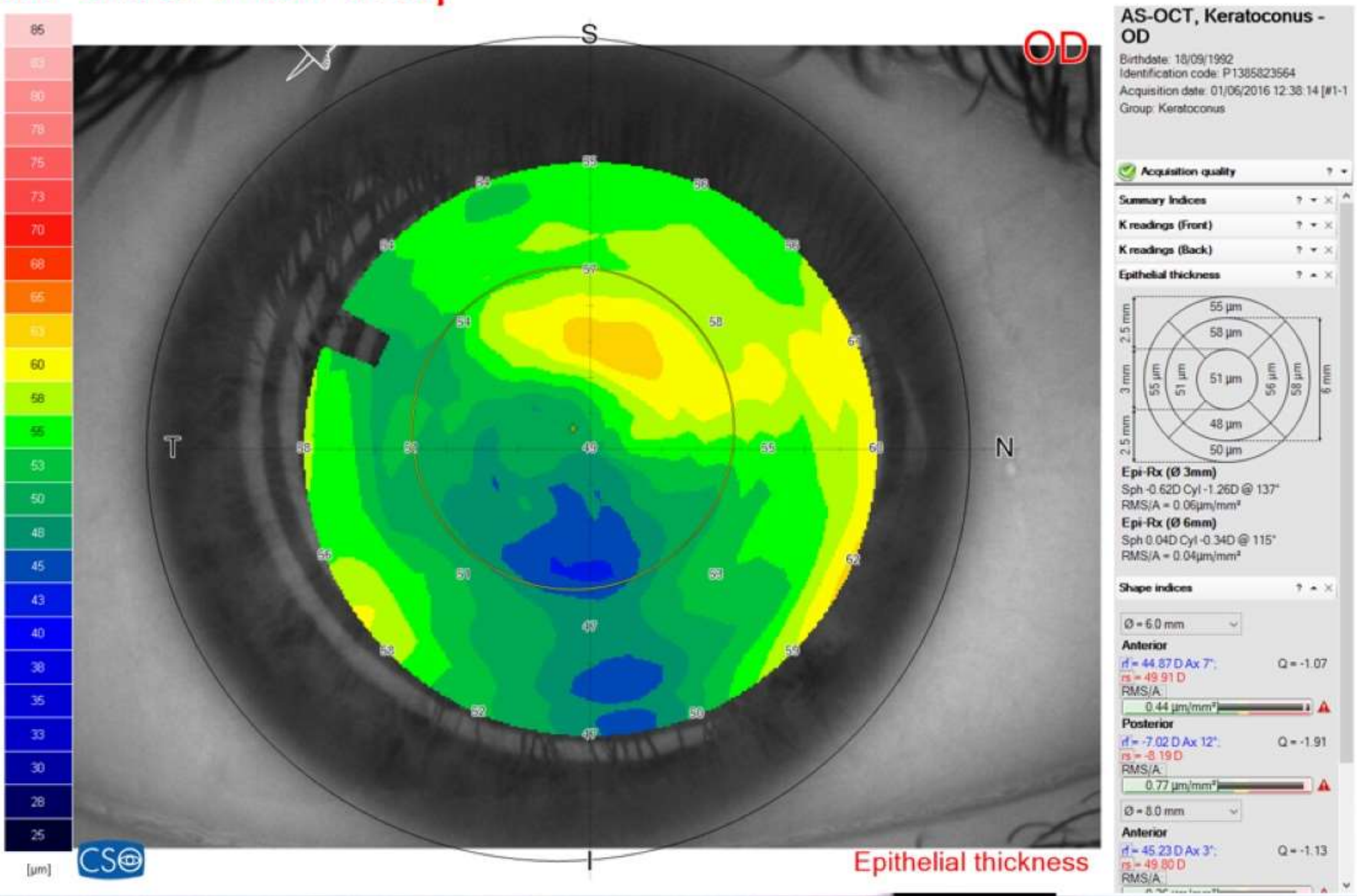
Old deep pre-descemetic stromal neovascularization + endothelial decompensation (see stromal thickening and stromal sub-epithelial opacities)
Courtesy of Dr.Claudio Macaluso

Anterior segment map

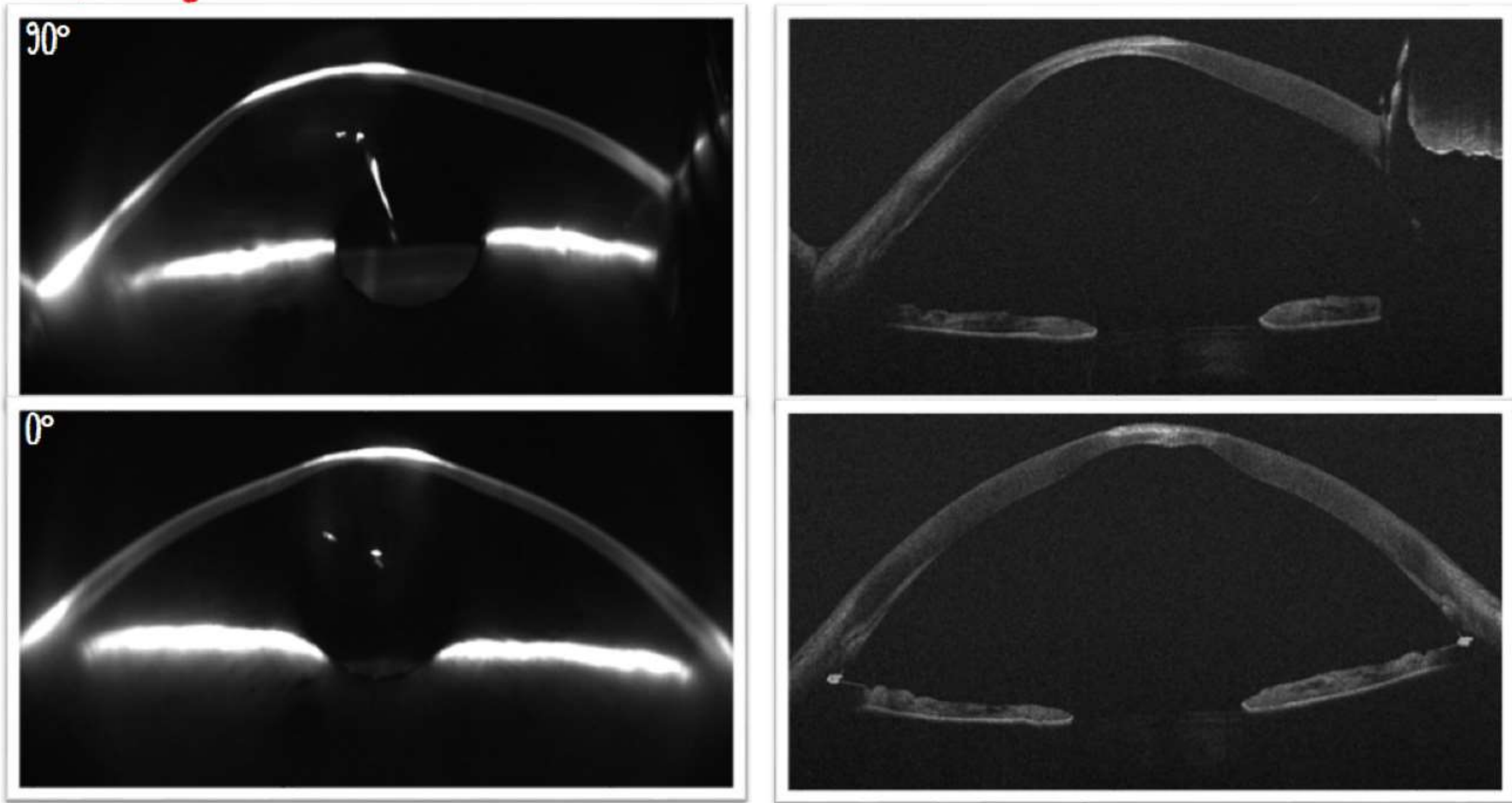


Corneal map | 3D radial scan (25 images) | 16 x 8.75 (1024 Ascans) | < 1 s | Raw

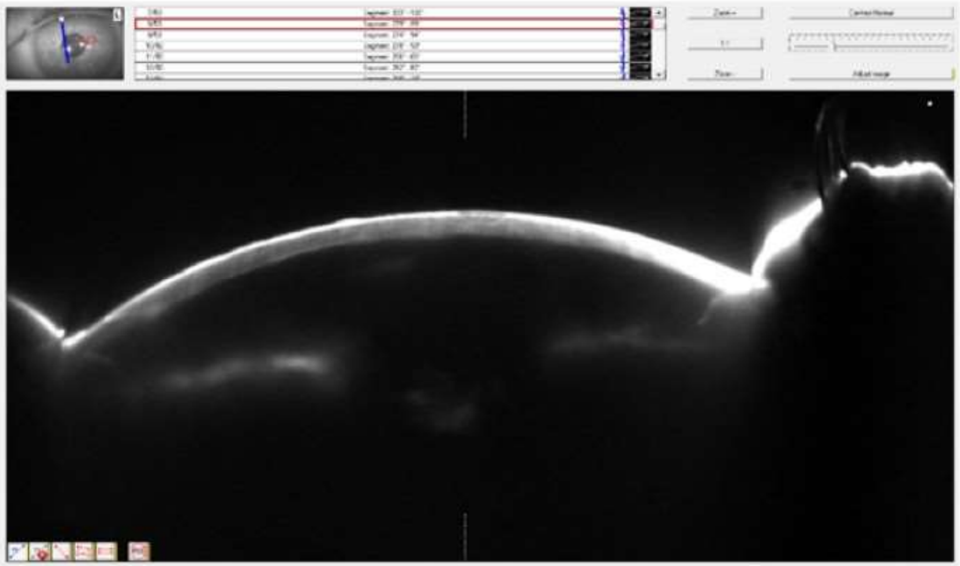
Epithelial thickness map

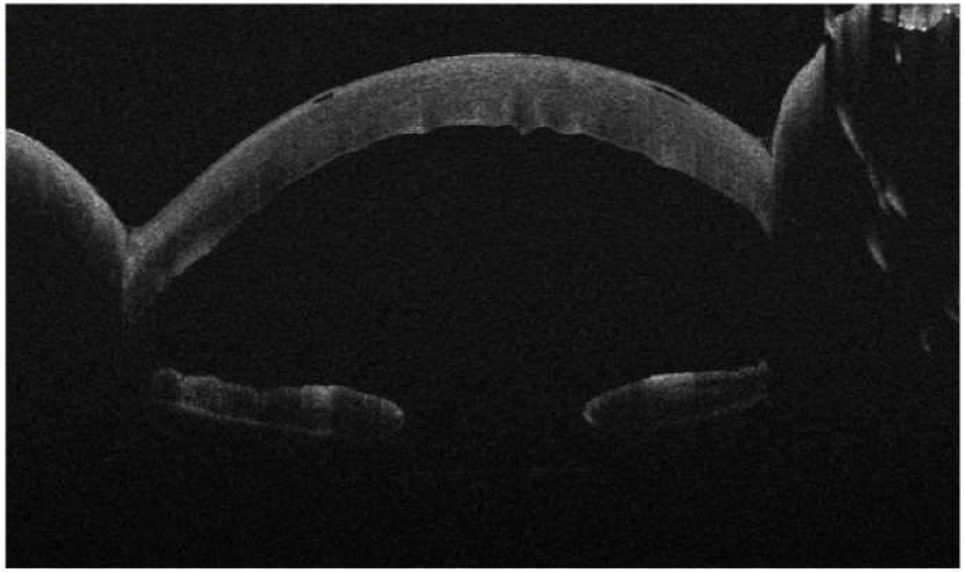


Scheimpflug vs. OCT



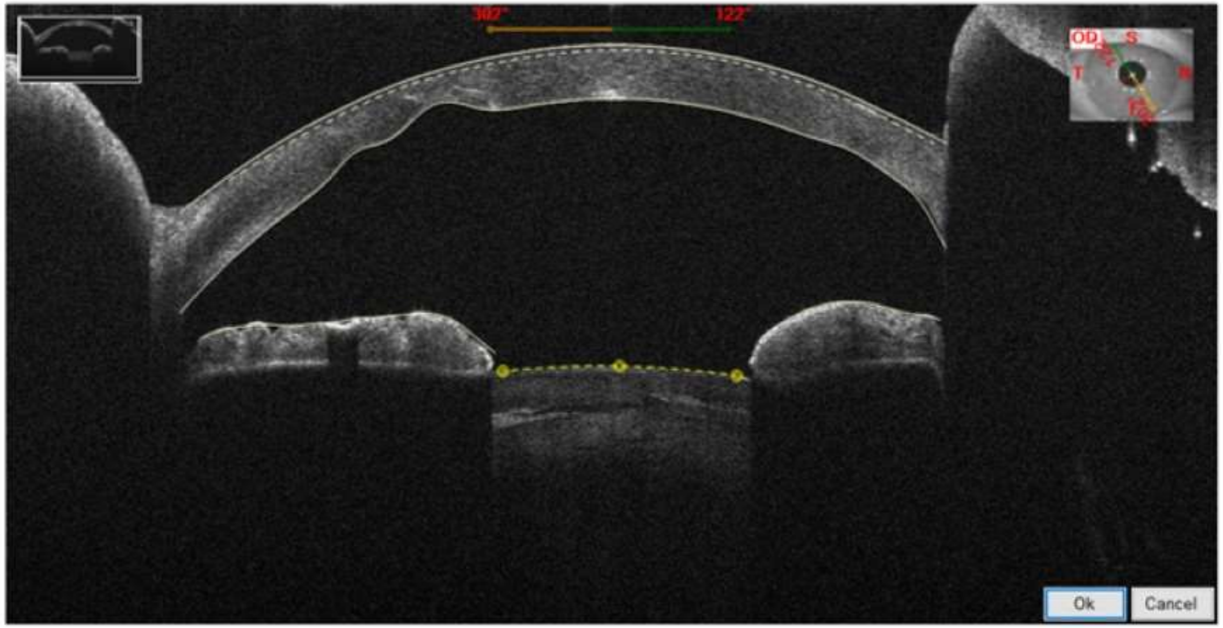
Scheimpflug vs. OCT

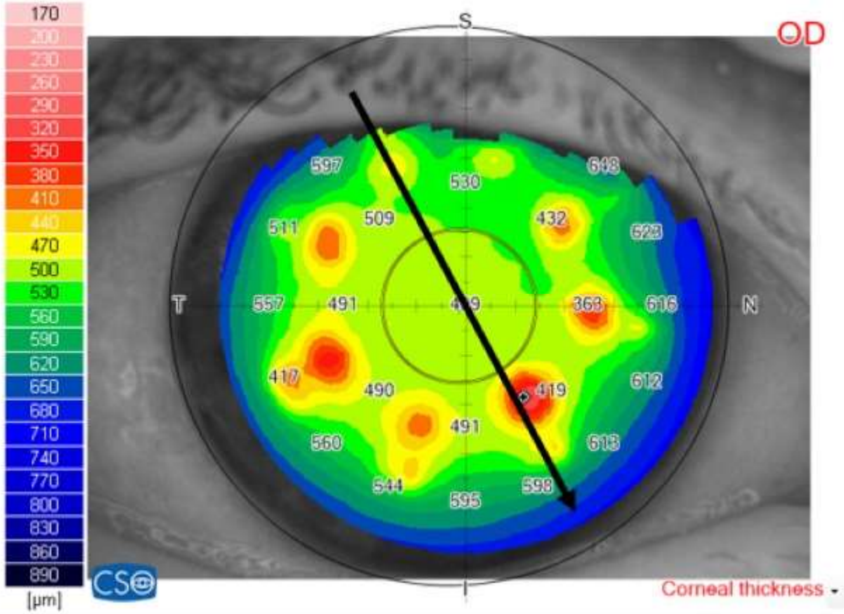




Pseudophakic Corneal edema:
"MS-39 OCT is helpful in confirming absence/presence of a Corneal scar, hence the decision of performing PKP or Endothelial keratoplasty is made easier"
Courtesy of Dr.Alaa Eldanasoury

Perfect corneal thickness even in critical eyes





Holmium laser thermal keratoplasy: Courtesy of Dr.Stanislao Rizzo

Spectral Domain vs. Swept Source

Swept Source

Spectral Domain

Faster (Higher A-scan rate)

Better SNR

Axial resolution

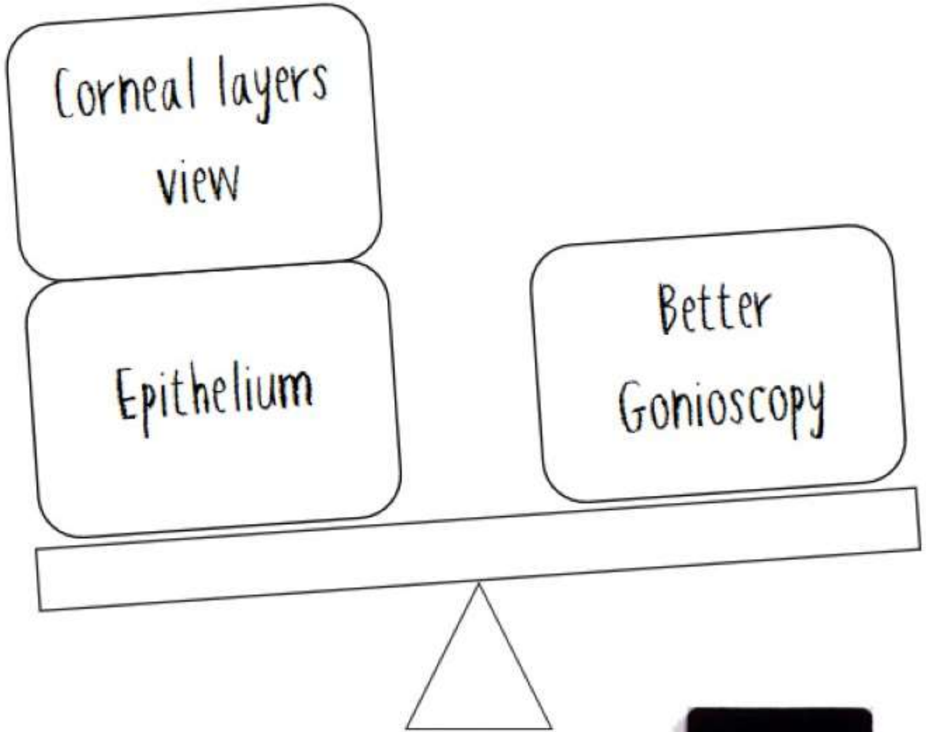
Image Depth

"AS-SS-OCT: not fully mature technology"

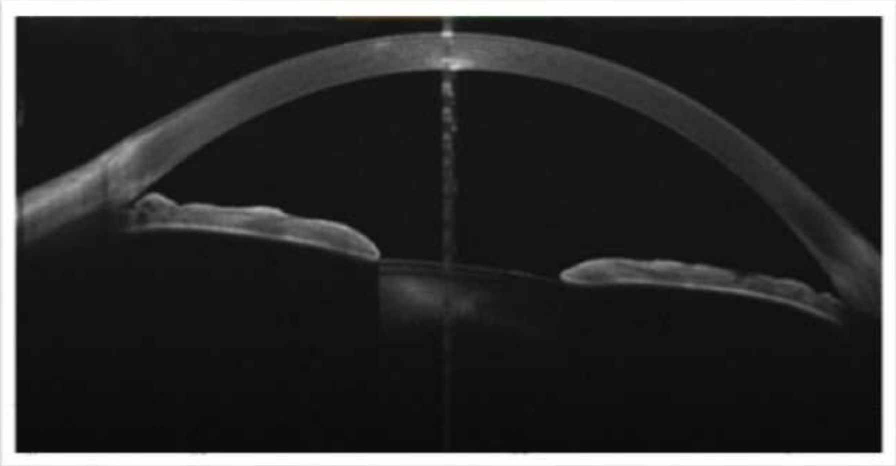
850nm vs. 1300nm

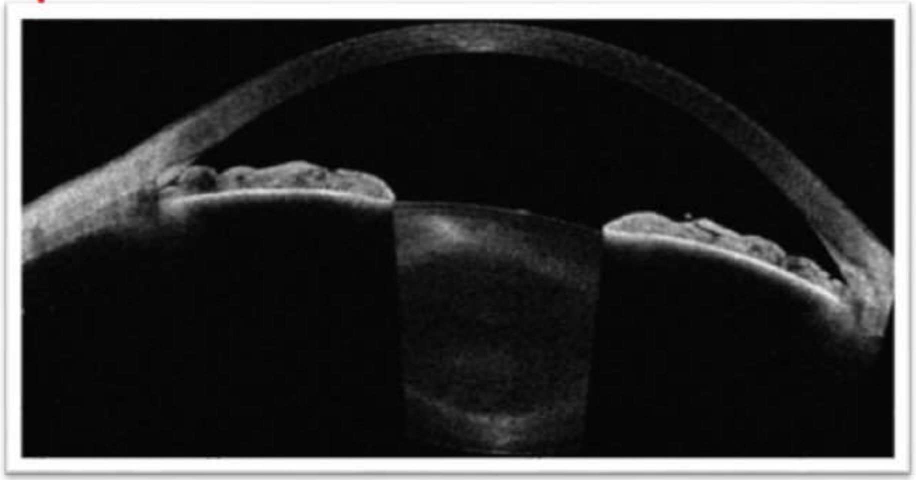
850nm

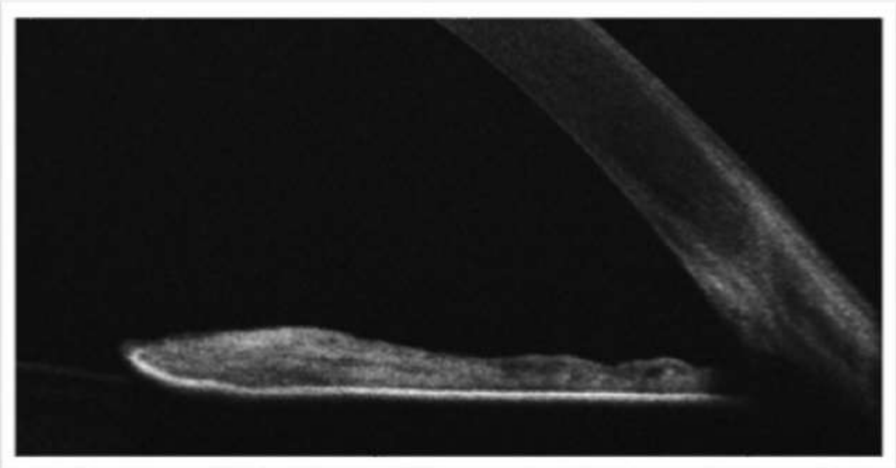
1300nm

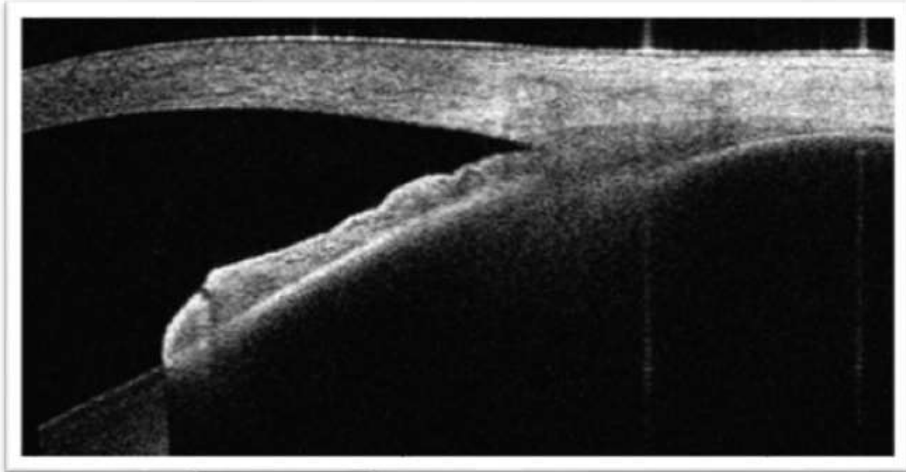


Spectral Domain (850nm) vs. Swept Source (1300nm)









Corneal topography: maps

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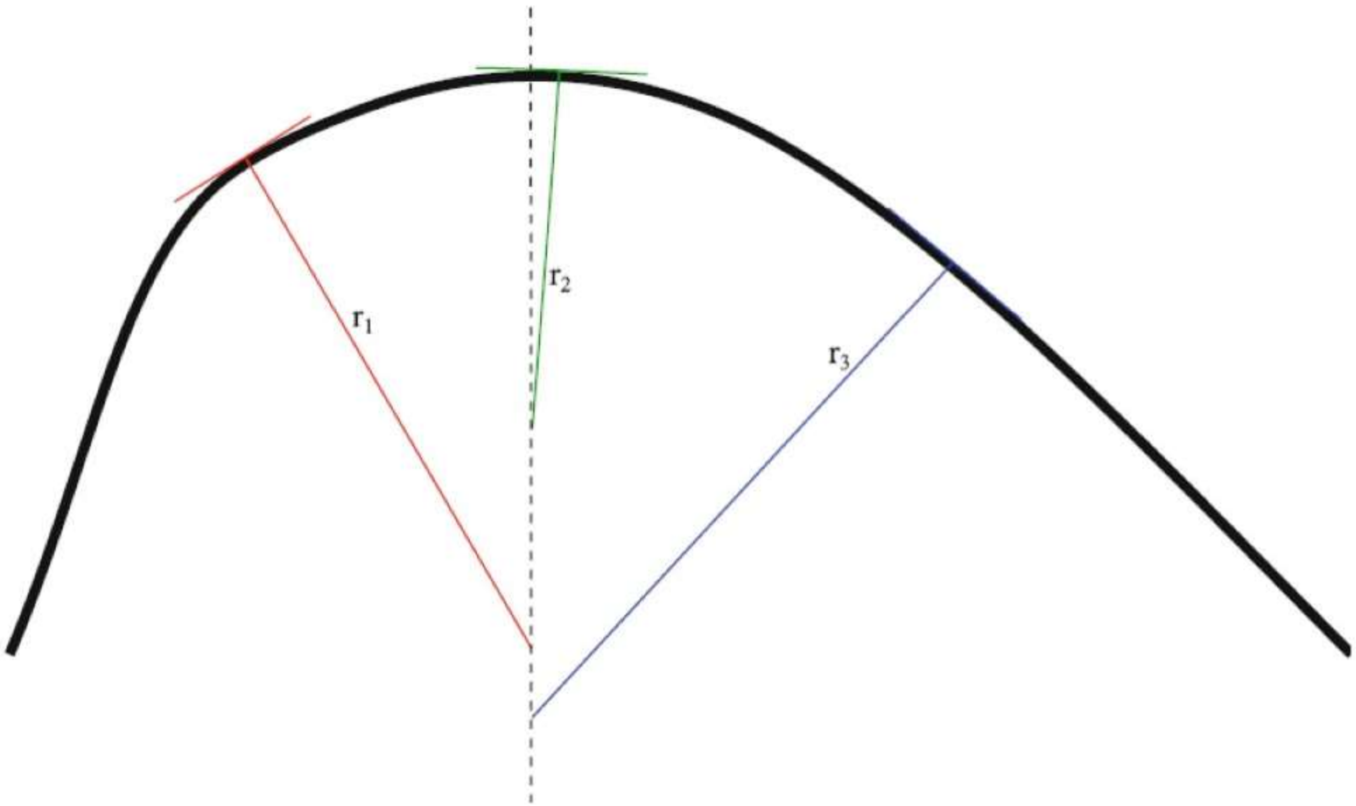
Sagittal (Axial) curvature map



Measures, in mm or in D, the radius of circles in each point of each meridian tangential to the cornea with their center bound to the keratoscopic axis.

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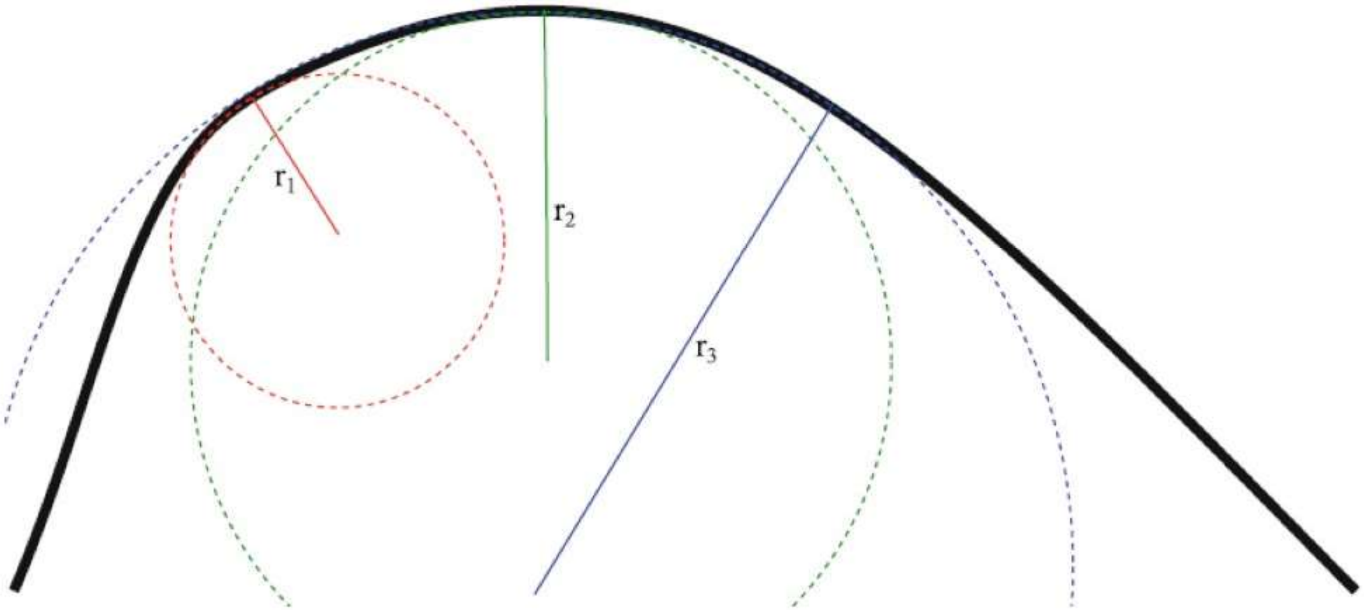
Tangential (Local or Istantaneous) curvature map



Measures, in mm or in D, the radius of curvature in each point of each meridian of local best approximating circles.

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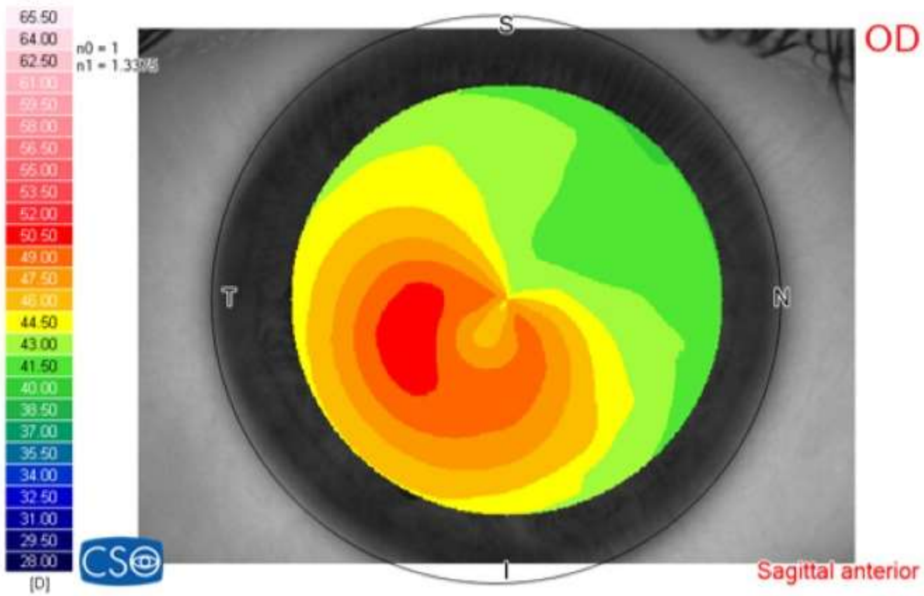
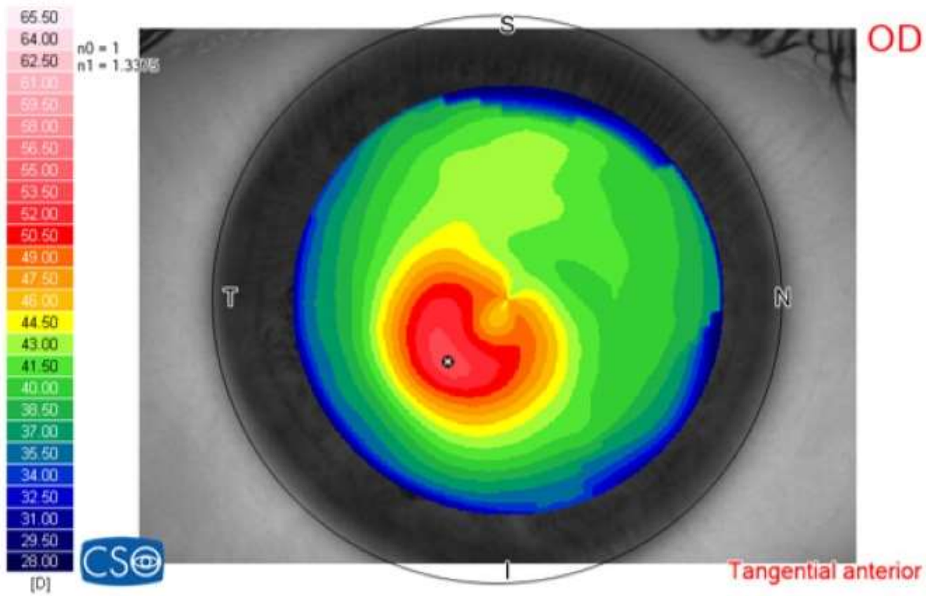
Tangential vs Sagittal





mm <==> D

- Tangential and Sagittal Curvature maps measure radii and not dioptric power
- In paraxial conditions $R_{[D]} = (n_1 - n_0)/R_{[mm]}$ can be used as an approximation of corneal dioptric power.

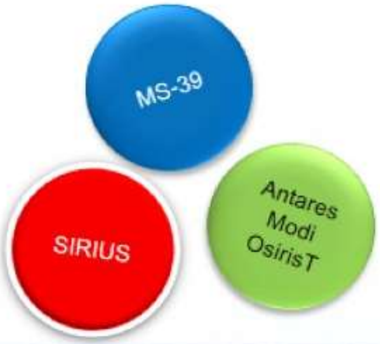
For anterior surface we can use (depending on n_1):

$$R_{[D]} = 10^3(n_{cornea} - n_{air})/R_{[mm]} = 10^3(1.3375 - 1)/R_{[mm]} = 337.5/R_{[mm]}$$

$$R_{[D]} = 10^3(n_{stroma} - n_{air})/R_{[mm]} = 10^3(1.376 - 1)/R_{[mm]} = 376/R_{[mm]}$$

For posterior surface:

$$R_{[D]} = 10^3(n_{cornea} - n_{air})/R_{[mm]} = 10^3(1.336 - 1.376)/R_{[mm]} = -40/R_{[mm]}$$



Corneal thickness

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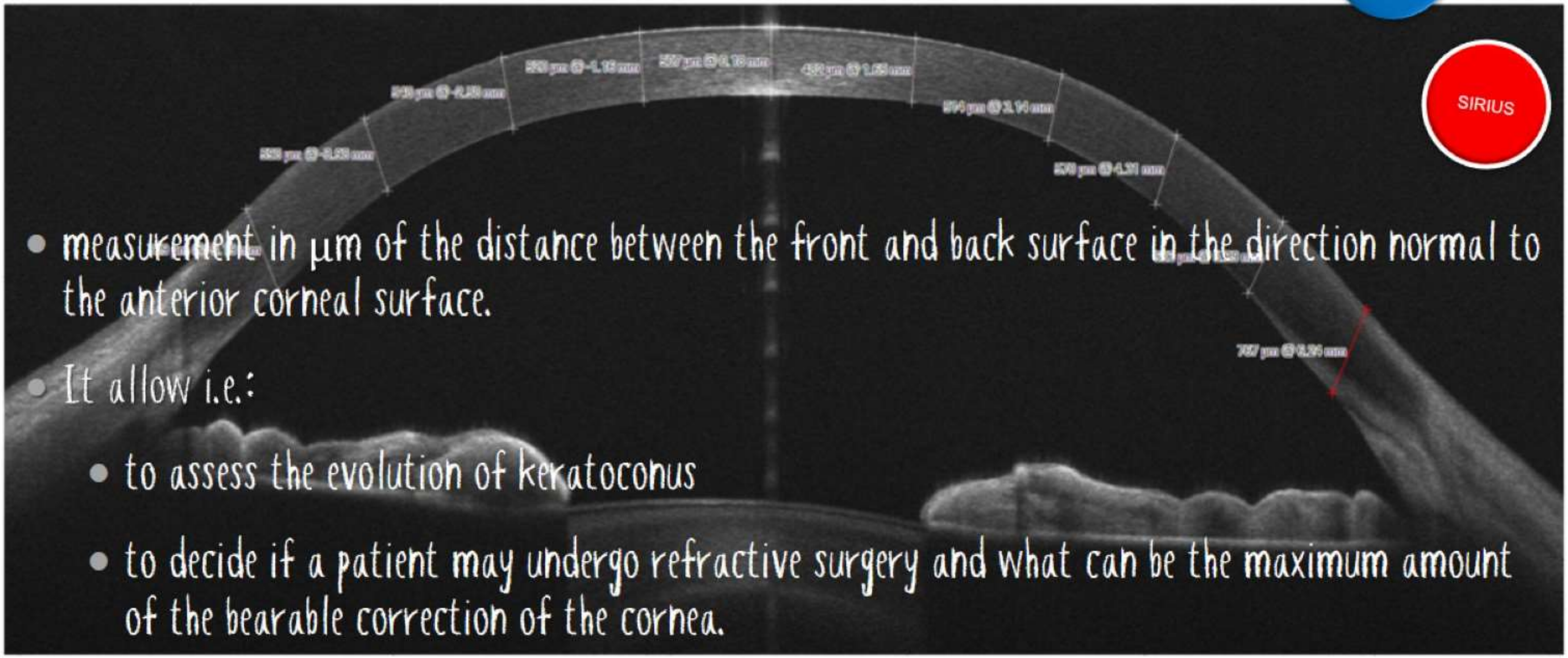
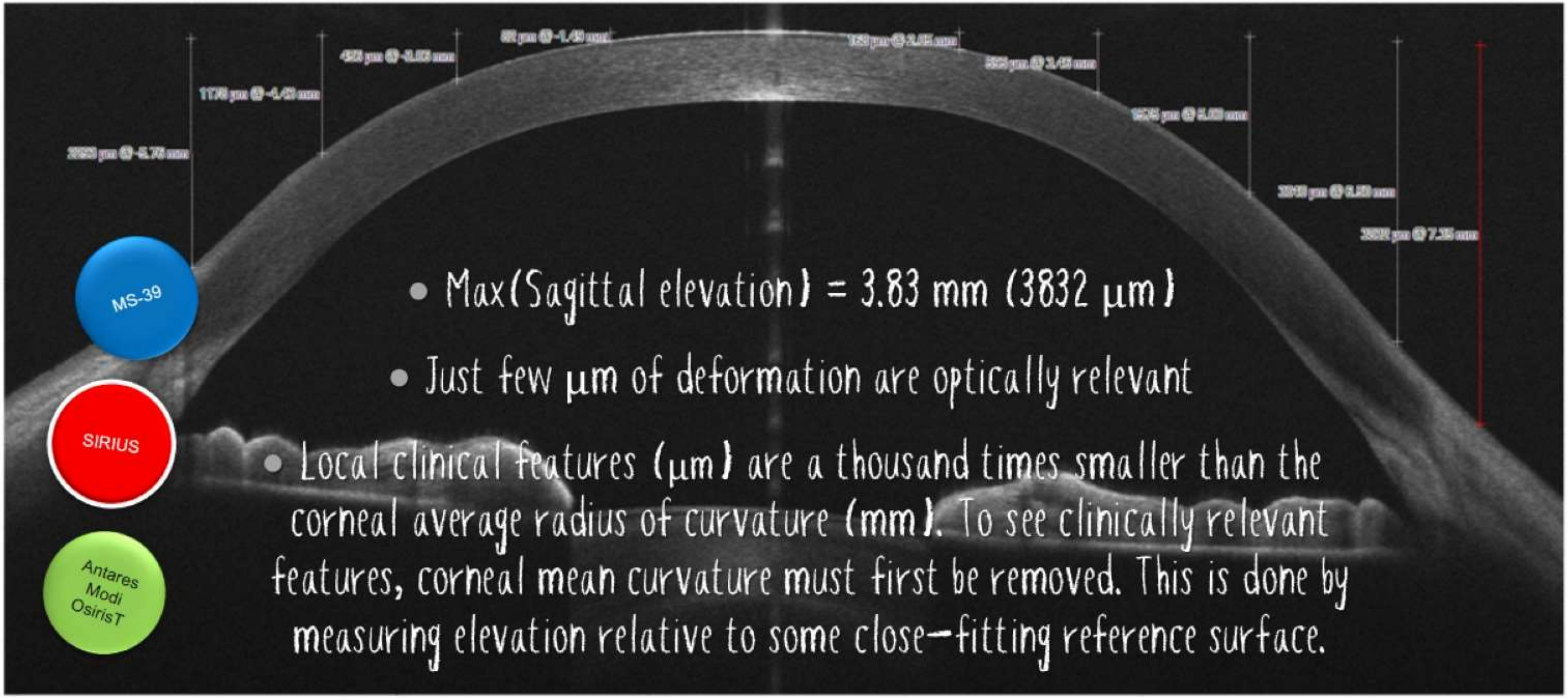


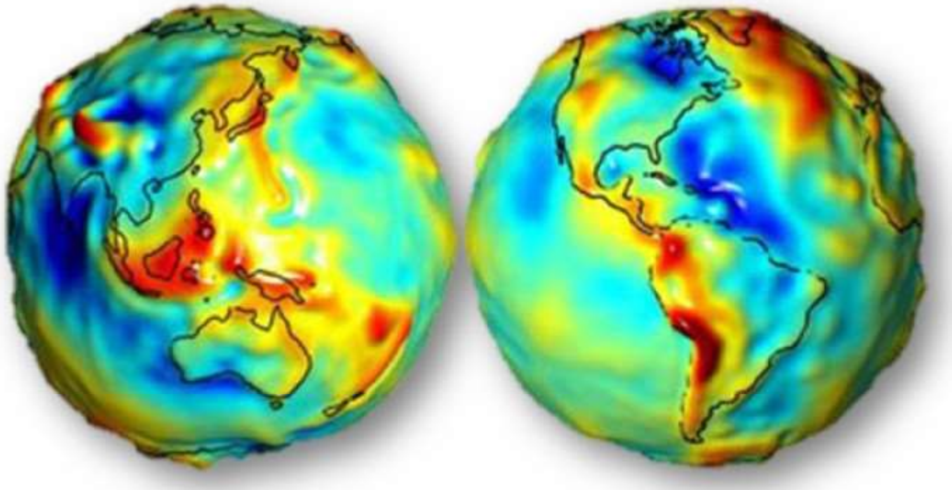
- measurement in μm of the distance between the front and back surface in the direction normal to the anterior corneal surface.
- It allow i.e.:
  - to assess the evolution of keratoconus
  - to decide if a patient may undergo refractive surgery and what can be the maximum amount of the bearable correction of the cornea.

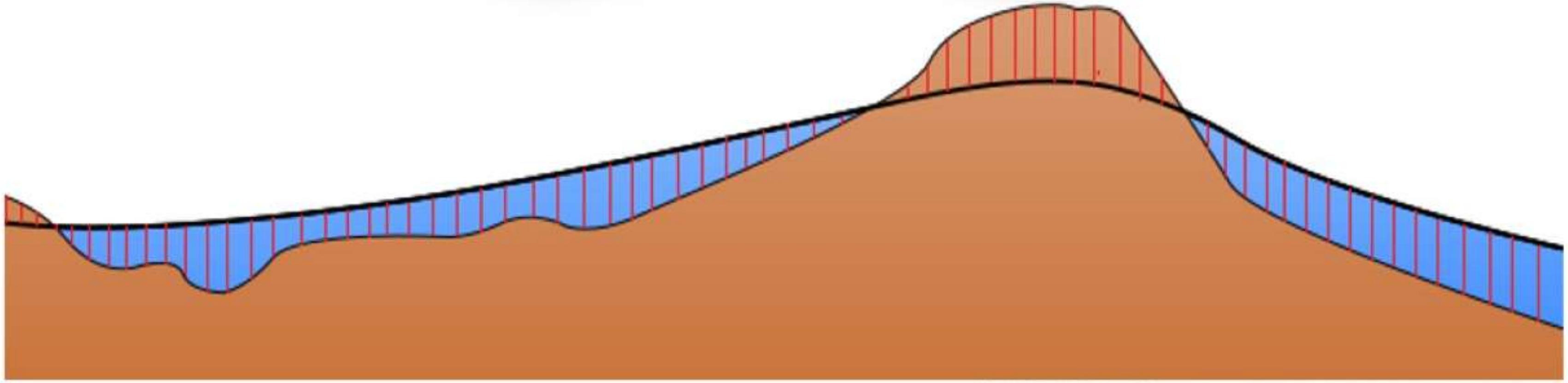
Elevations



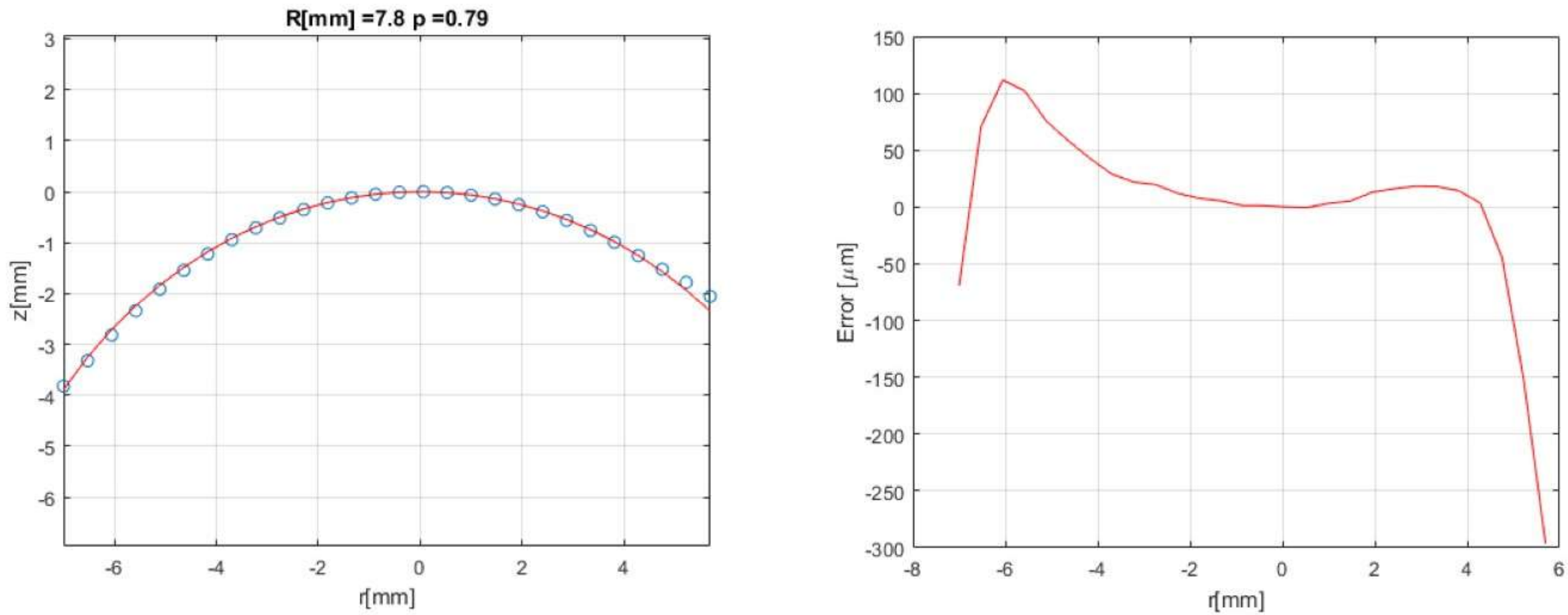
- Max(Sagittal elevation) = 3.83 mm (3832 μm)
- Just few μm of deformation are optically relevant
- Local clinical features (μm) are a thousand times smaller than the corneal average radius of curvature (mm). To see clinically relevant features, corneal mean curvature must first be removed. This is done by measuring elevation relative to some close-fitting reference surface.

Geoid

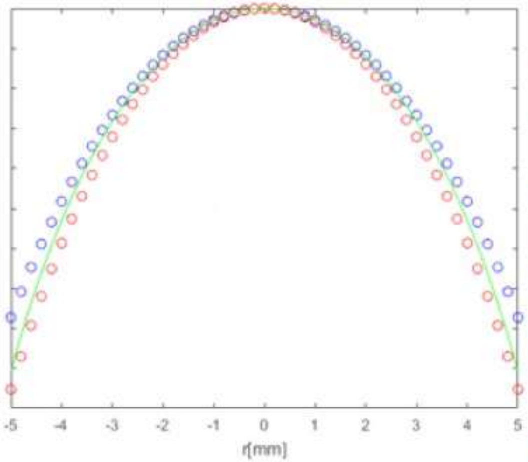


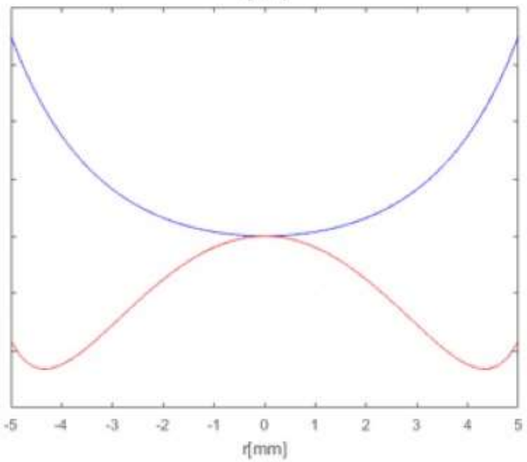


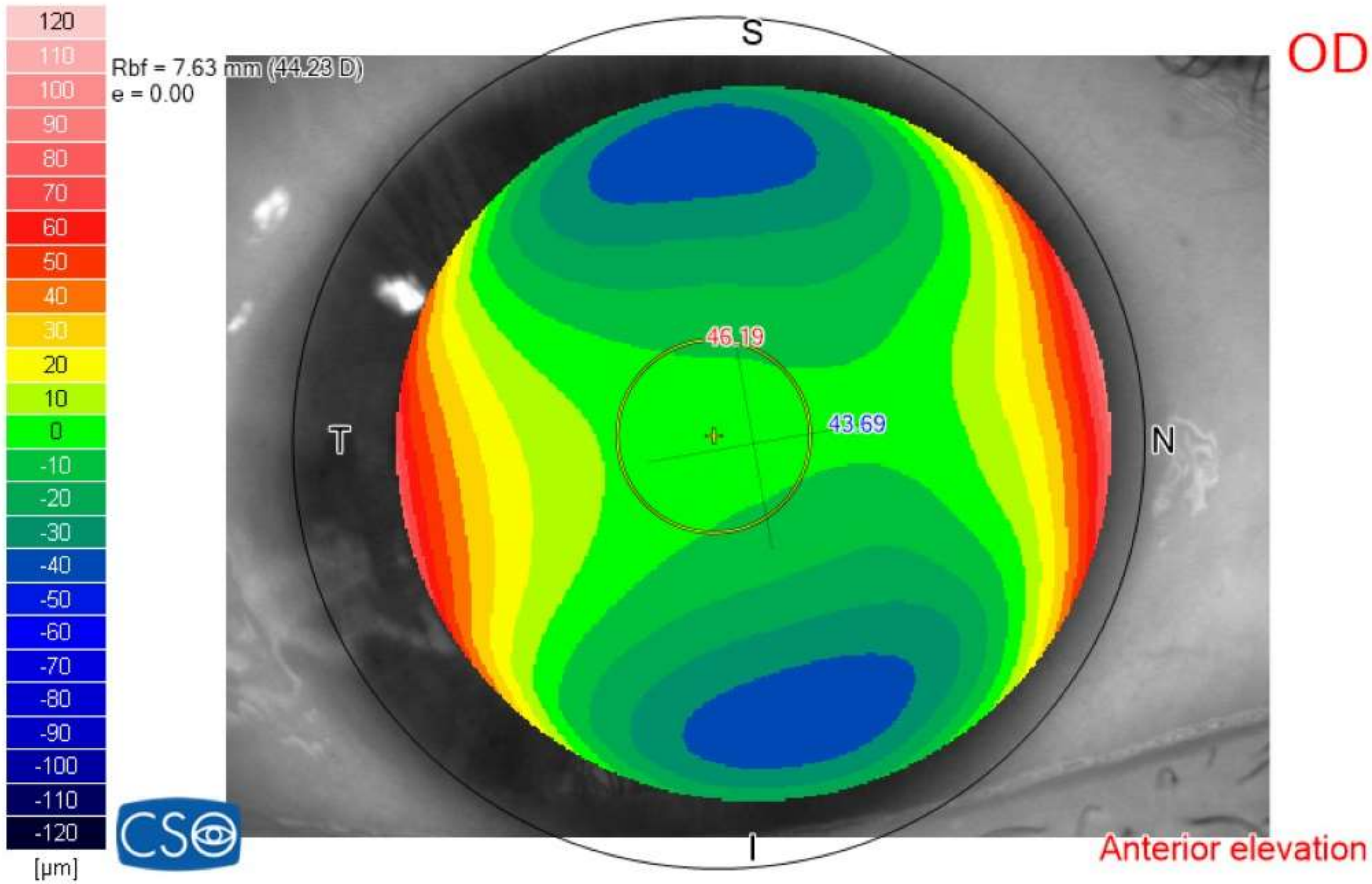
Elevations: measured samples and fitting curves



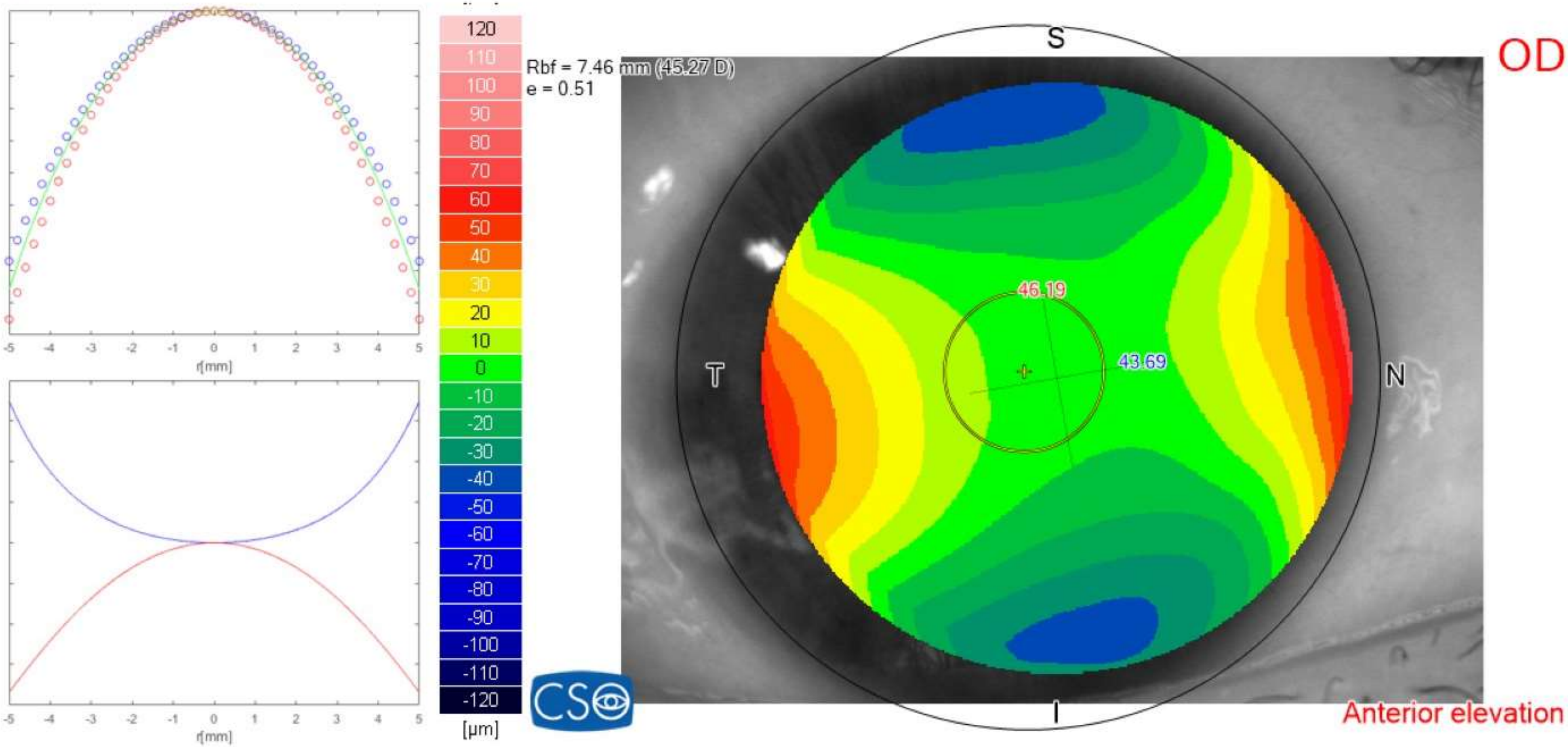
Spherical reference



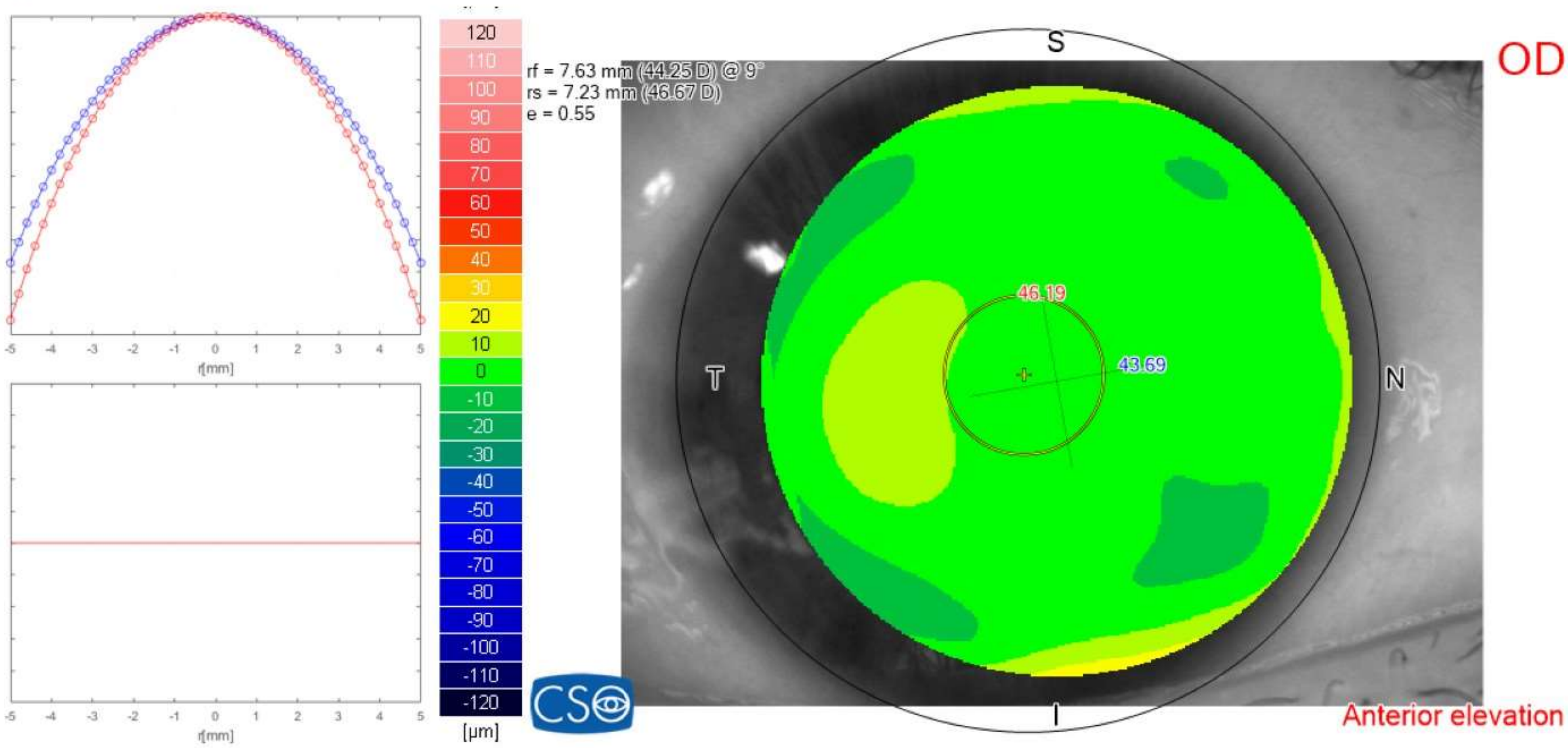




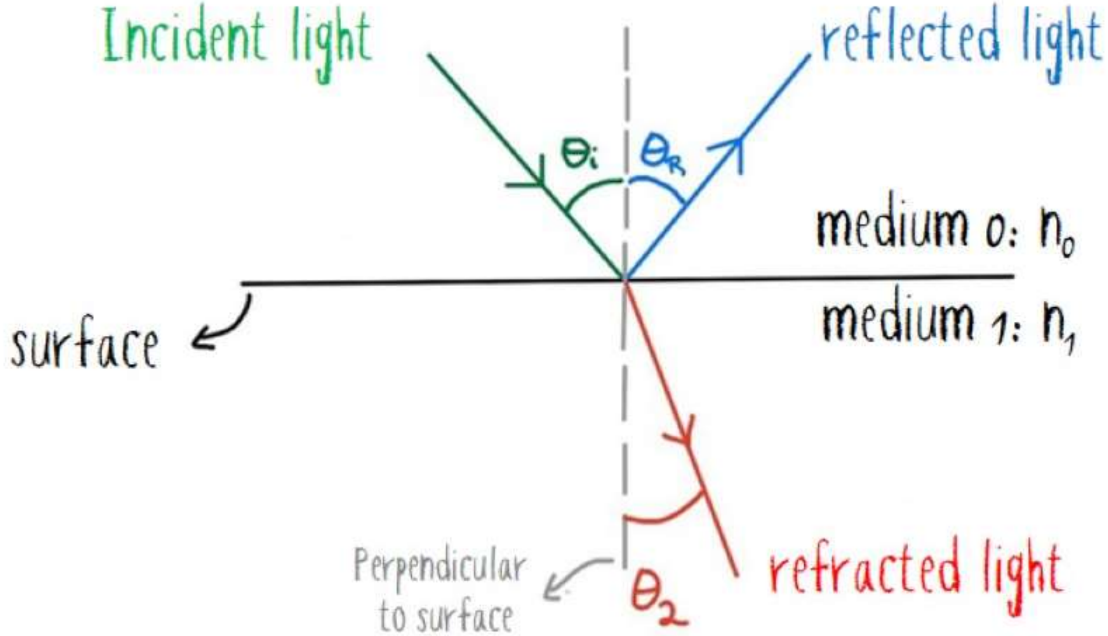
Aspherical reference



Aspherotoric reference



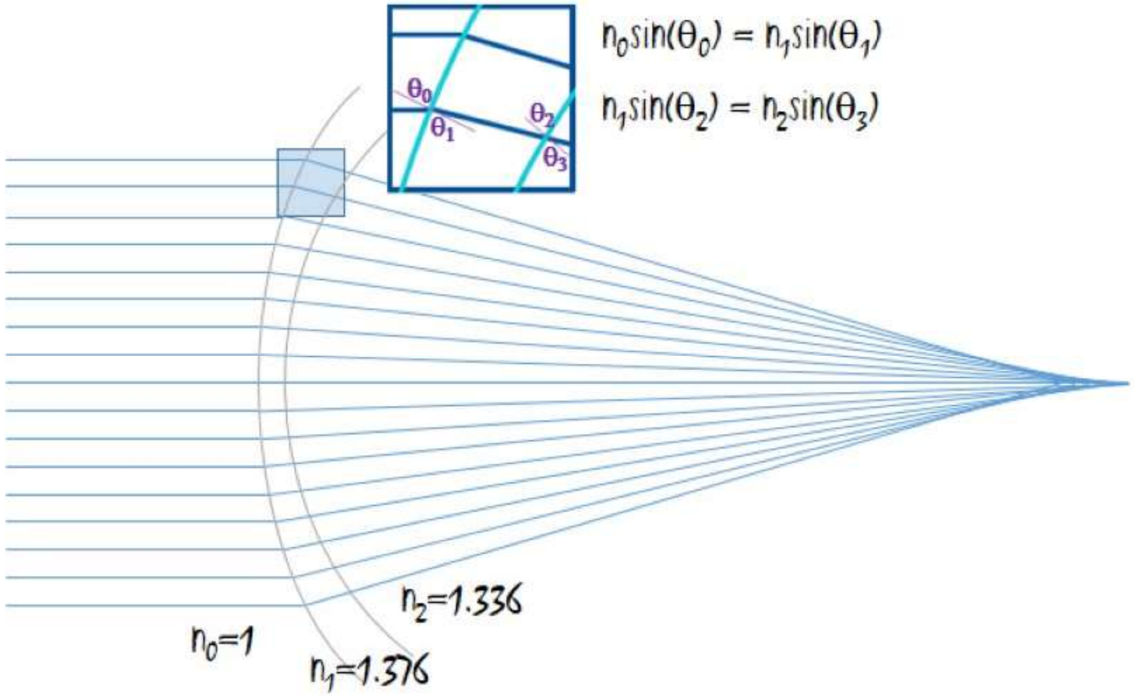
RayTracing: Snell's law



$$\theta_1 = \theta_R$$

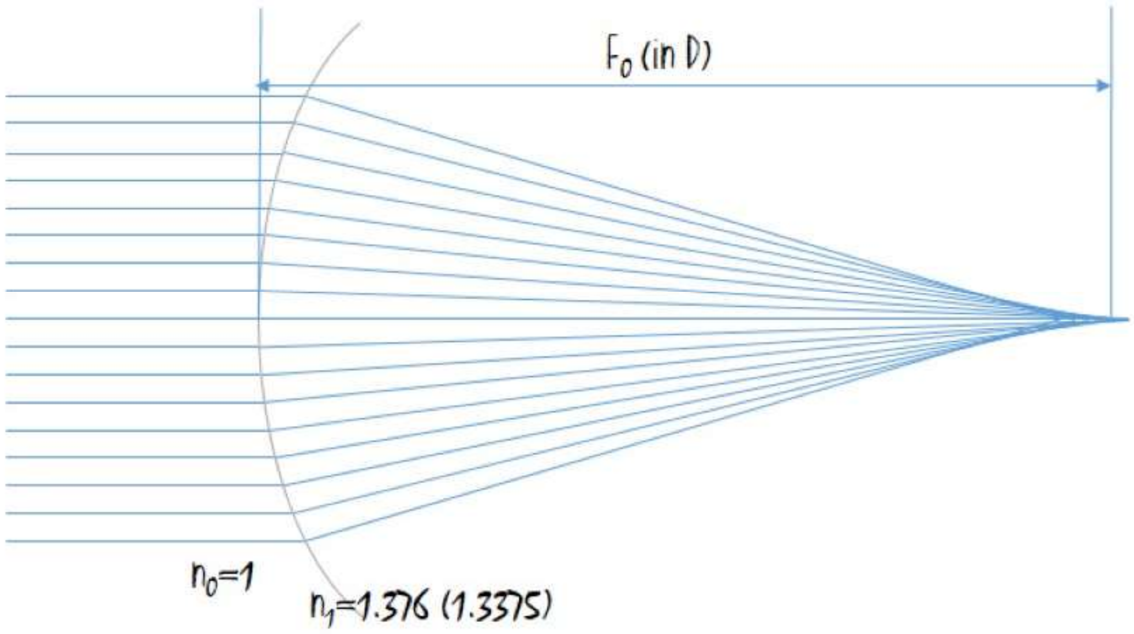
$$n_0 \sin(\theta_1) = n_1 \sin(\theta_2)$$

RayTracing



θ_0
θ_1
θ_2
θ_3
$n_0 \sin(\theta_0) = n_1 \sin(\theta_1)$
$n_1 \sin(\theta_2) = n_2 \sin(\theta_3)$
$n_2=1.336$
$n_0=1$
$n_1=1.376$

Refractive anterior power



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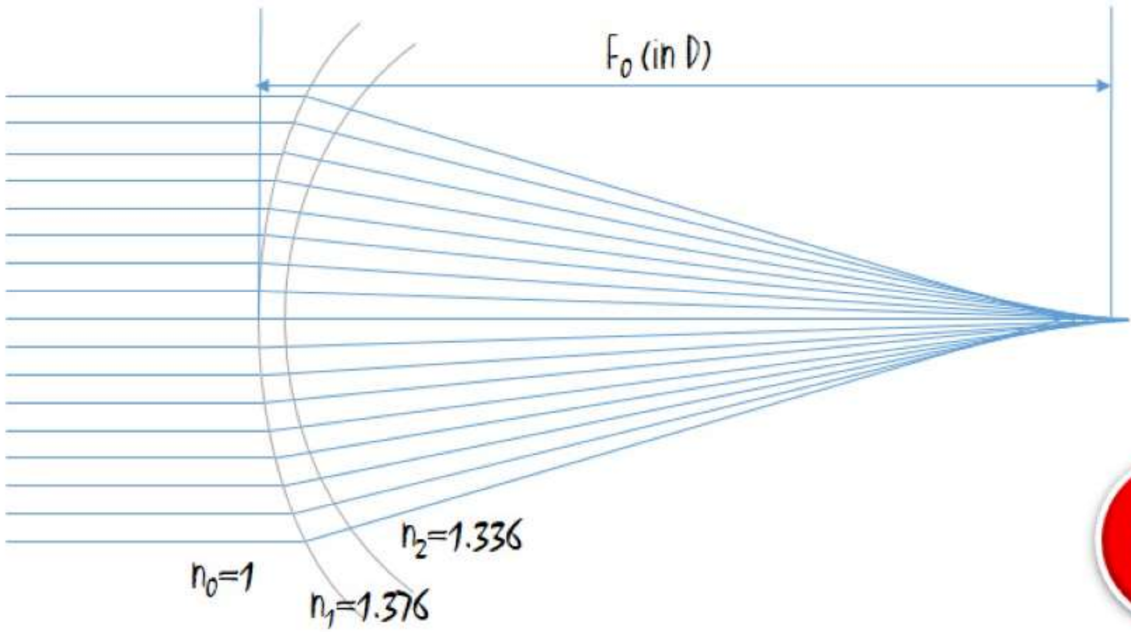
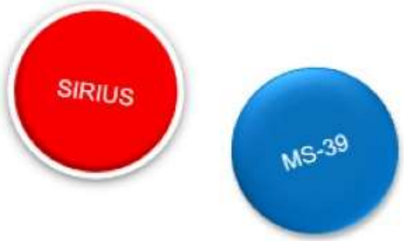
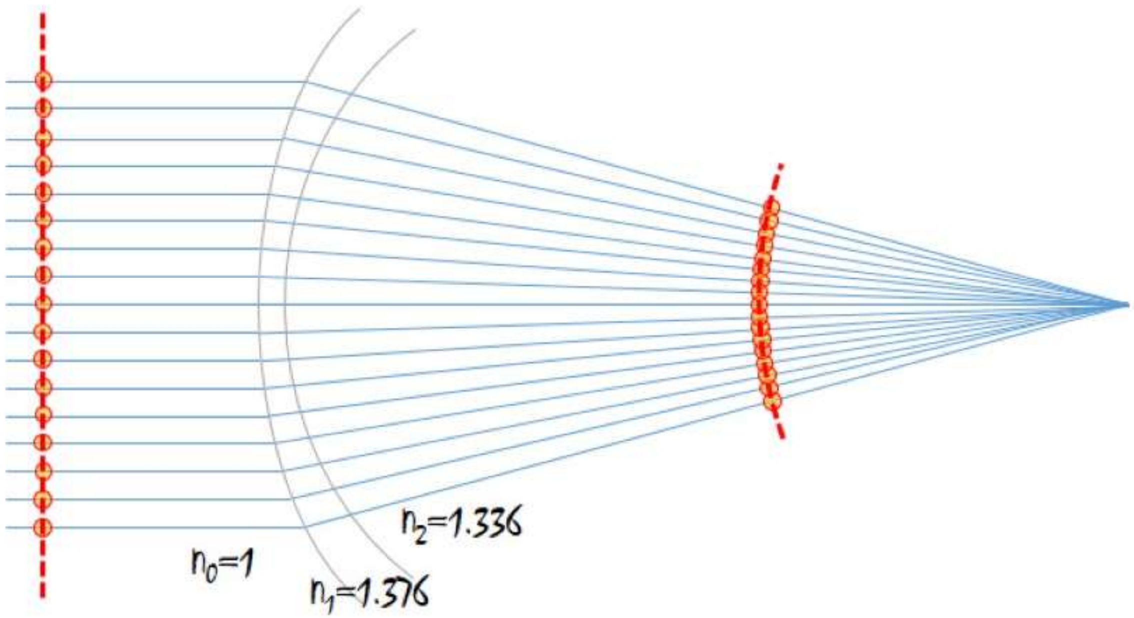
Refractive equivalent power



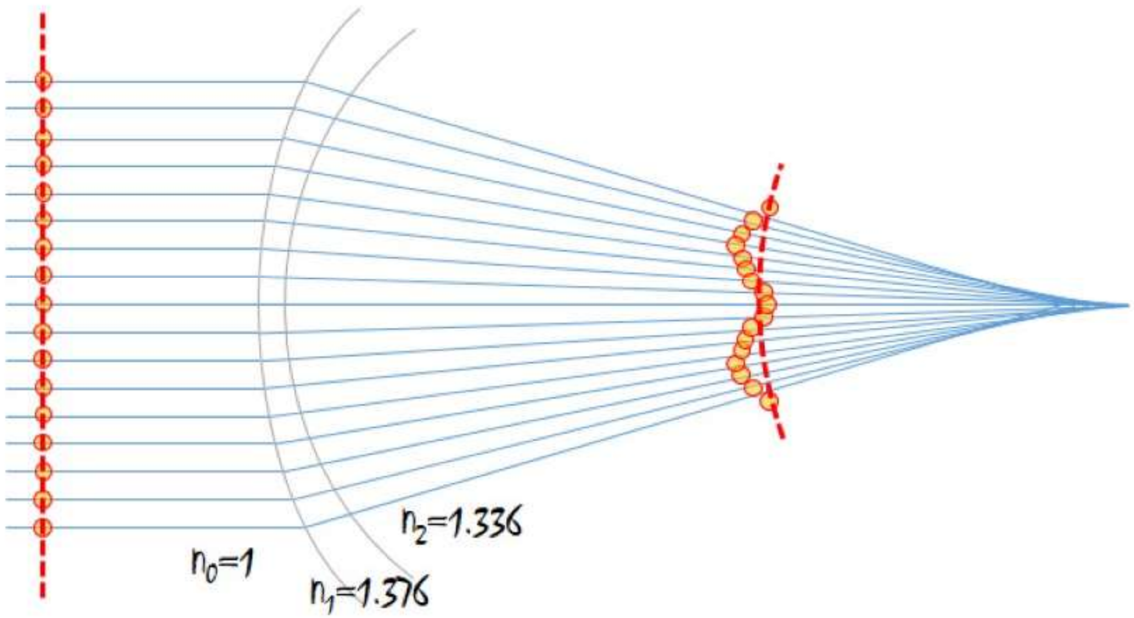


Refractive posterior power = Refr. equivalent pwr – Refr. anterior pwr

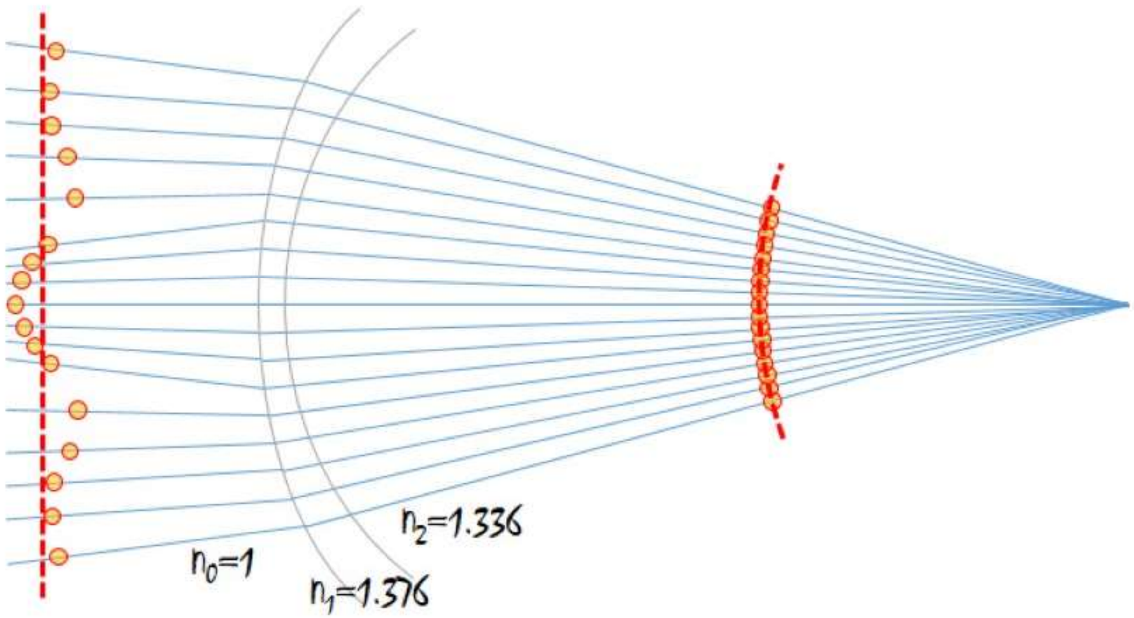
Wave Front: ideal condition



Optical Path Distance



Wave Front Error = -Optical Path Distance



Wavefront analysis: Zernike's decomposition

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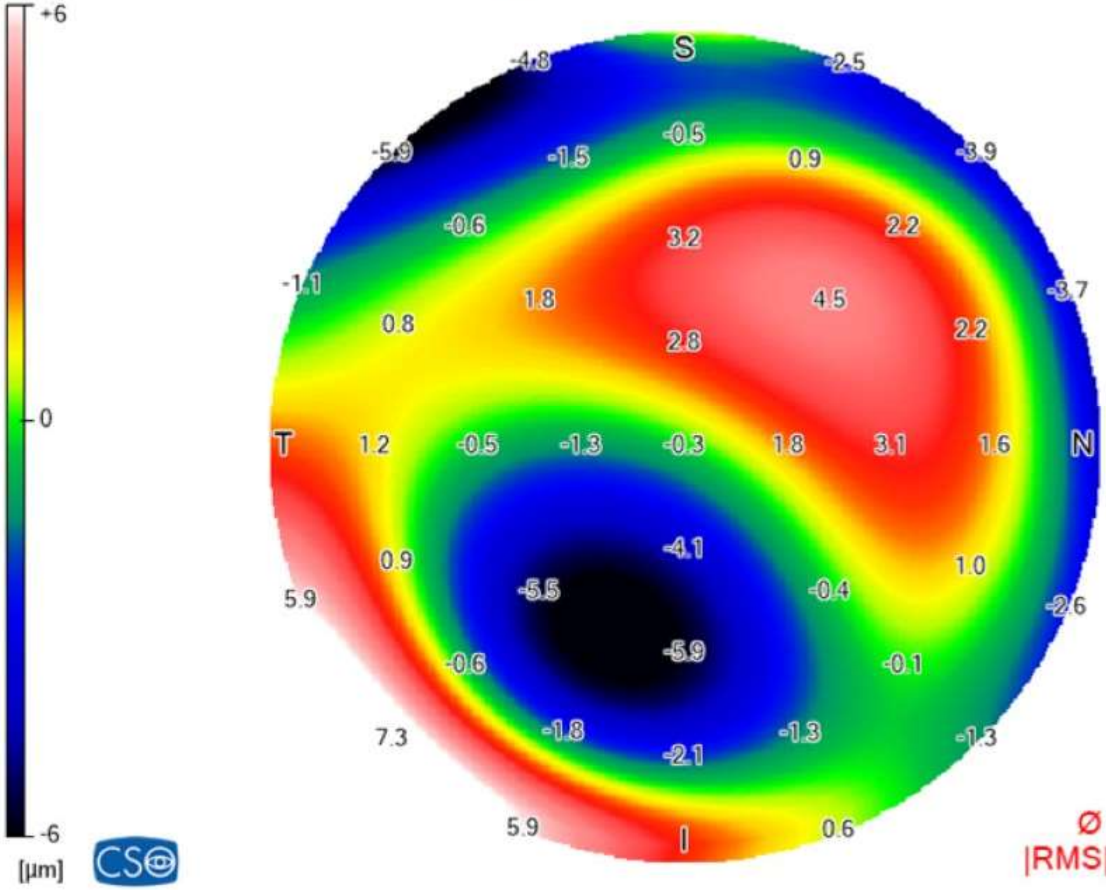
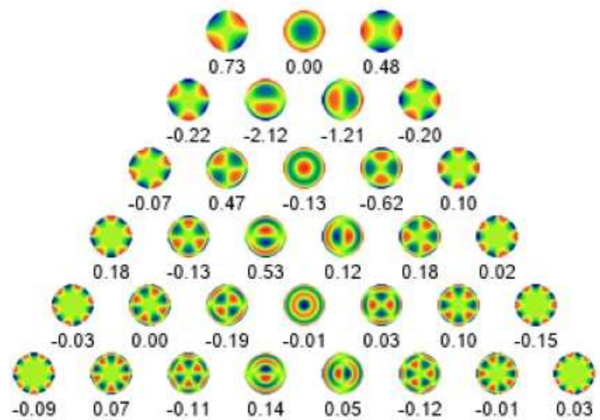


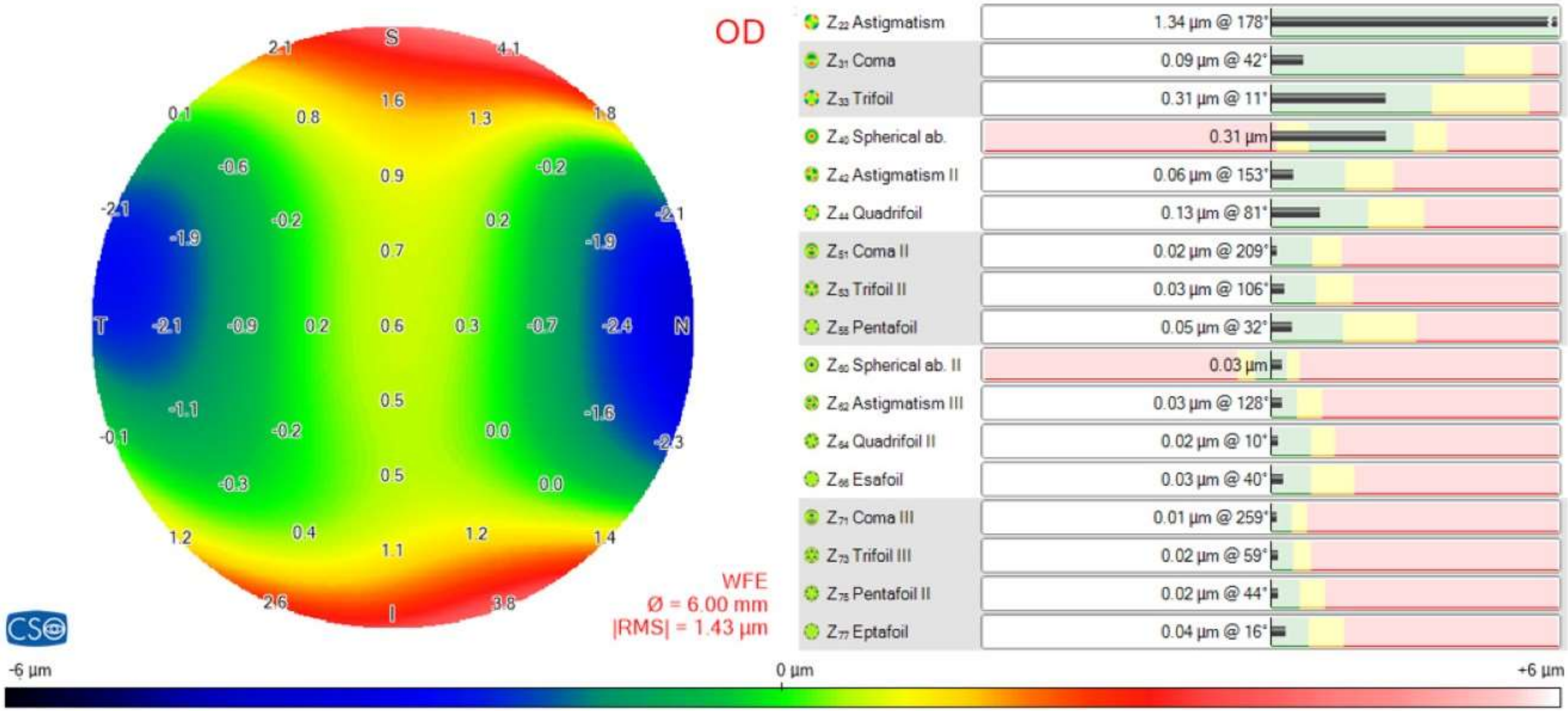
WFE
Ø = 6.00 mm
|RMS| = 2.82 µm

RMS [µm]

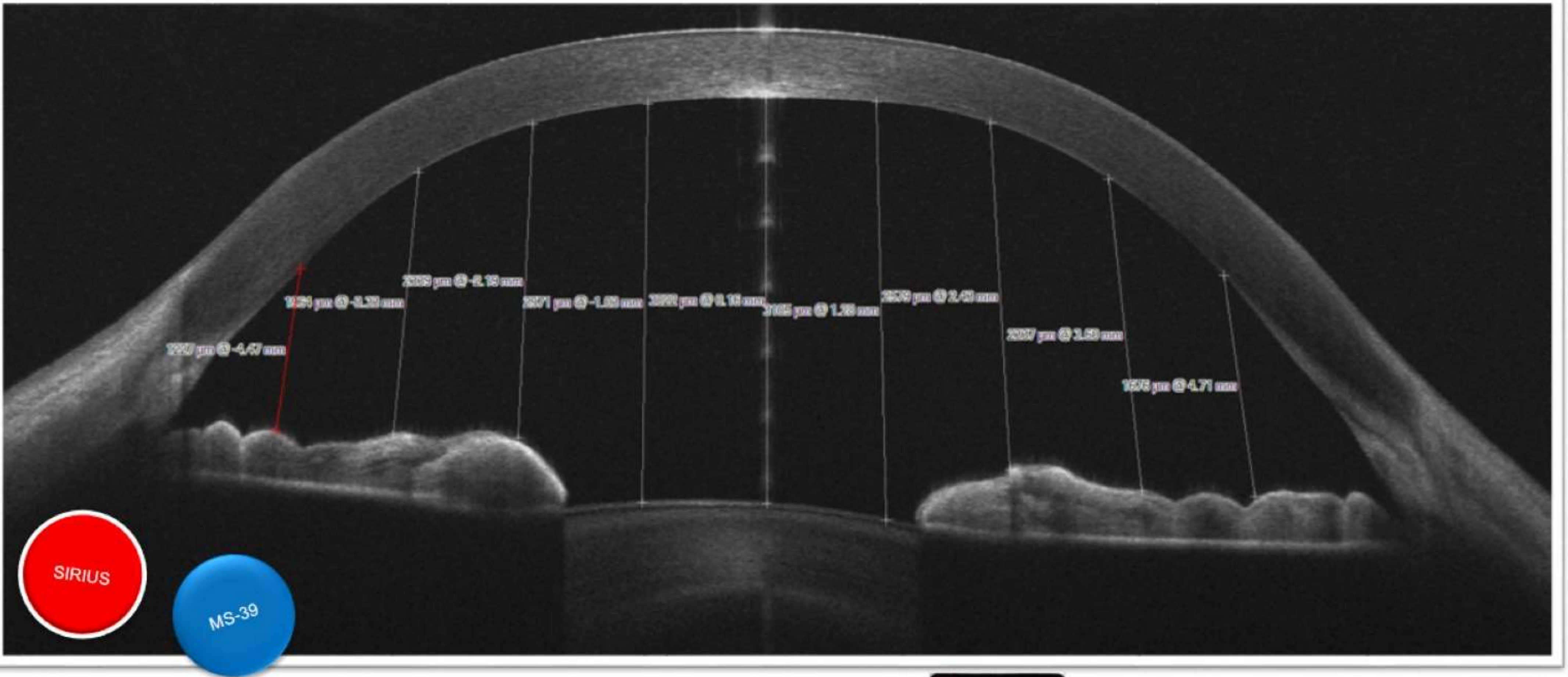
Total = 2.82 LOA = 0.87 HOA = 2.68



Wave Front Error = -Optical Path Distance



Anterior Chamber Depth



Corneal topography: indices

Gabriele Vestri

Francesco Versaci

Indices

Antares Modi OsirisT

- Summary indices
- K-readings anterior (*Sim-K, Meridians, Hemi-meridians, Peripheral degrees*)
- Shape indices
- Keratorefractive indices
- Keratoconus screening

SIRIUS

- Summary indices
- K-readings anterior (*Sim-K, Meridians, Hemi-meridians, Peripheral degrees*)
- K-readings posterior (*Meridians, Hemi-meridians, Peripheral degrees*)
- Shape indices
- Refractive analysis
- Keratoconus screening

MS-39

- Summary indices
- K-readings anterior (*Sim-K, Meridians, Hemi-meridians, Peripheral degrees*)
- K-readings posterior (*Meridians, Hemi-meridians, Peripheral degrees*)
- Epithelial thickness
- Shape indices
- Refractive analysis
- Keratoconus screening

Useful tip (Limbus and ICL sizing)

- The measurement of limbus is not an accurate measurement by definition, as there is no sharp transition between cornea and sclera.
- CSO's former measurements of HVID were (in average) 0.35 mm longer than the measurements done with Orbscan
- The measurement of limbus is widely and (wrongly) used for ICL sizing in formulas
- Traditional ICL sizing formulas were adjusted using Orbscan data
- In order to allow doctors to use traditional ICL sizing formulas, adjusted HVID is provided too
- It can be chosen from the window Options--> Miscellaneous

K-Readings

- Based on front sagittal curvature map
  - Sim-k
  - Meridians (front) 3mm, 5mm or 7mm
  - Hemimeridians (front) 3mm, 5mm or 7mm
- Based on posterior sagittal curvature map
  - Meridians (back) 3mm, 5mm or 7mm
  - Hemimeridians (back) 3mm, 5mm or 7mm

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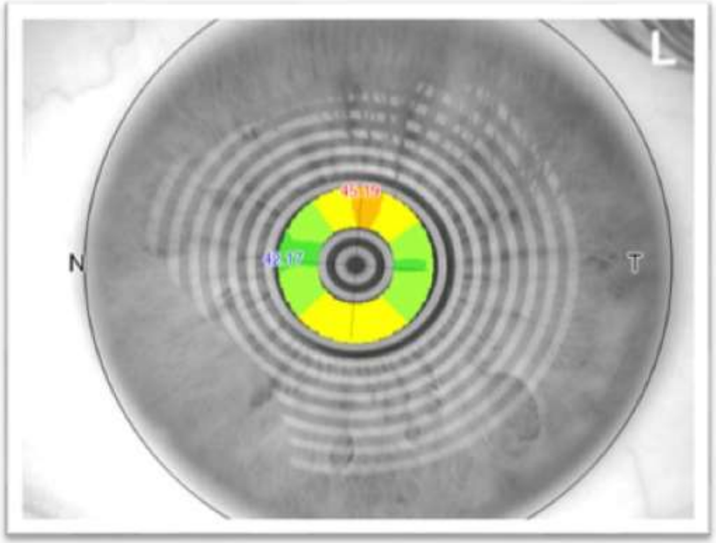
Sim-K (Simulated keratometry)

Simulates the measurement of a keratometer, returning the orthogonal pair of meridians with maximum cylinder in ring shaped zone (internal radius 1 mm, external radius 2 mm).

k1 = 42,17 D @ 176°
k2 = 45,19 D @ 86°
Avg = 43,63 D
Cyl = −3,02 D @ 176°



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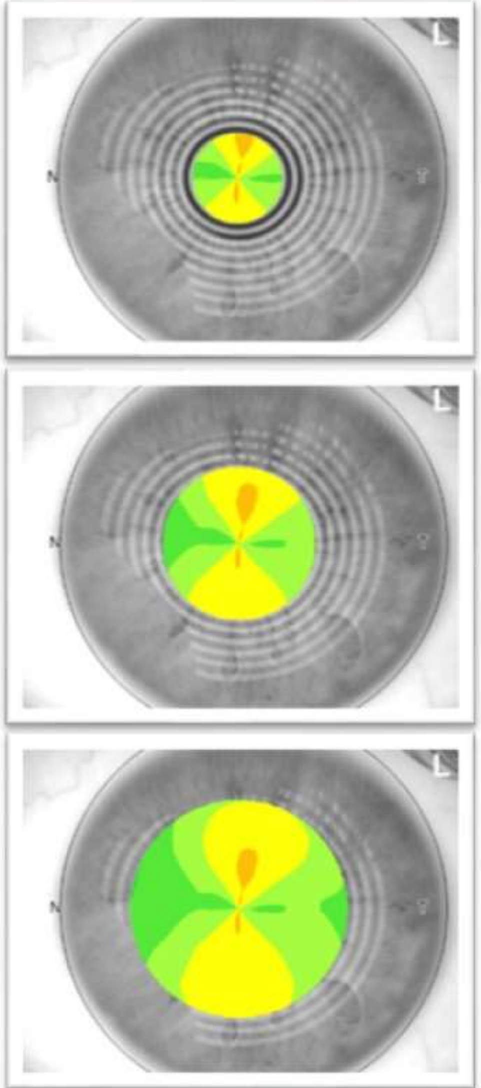
Meridians

Orthogonal pair of meridians with maximum cylinder, in the central 3mm, 5mm or 7mm of front (and eventually rear) sagittal curvature map.



3mm

k1 = 42,15 D @ 173°

k2 = 45,27 D @ 83°

Avg = 43,65 D

Cyl = −3,12 D @ 173°

5mm

k1 = 42,13 D @ 174°

k2 = 45,17 D @ 84°

Avg = 43,60 D

Cyl = −3,04 D @ 174°

7mm

k1 = 41,98 D @ 173°

k2 = 44,94 D @ 83°

Avg = 43,41 D

Cyl = −2,96 D @ 173°

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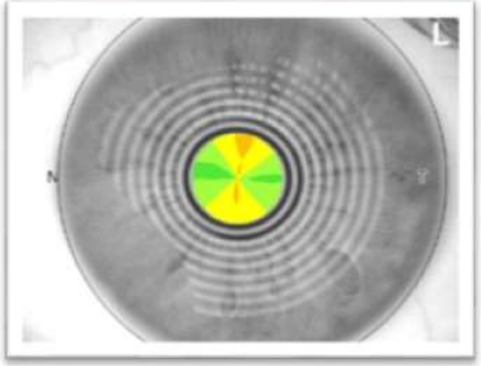
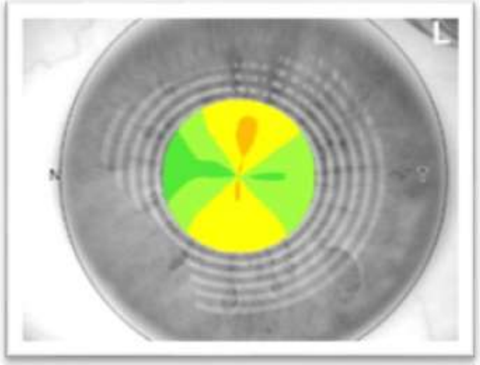
Hemi-meridians

Non-orthogonal double-pair of meridians (one flat and one steep), in the central 3mm, 5mm or 7mm of of front (and eventually rear) sagittal curvature map.



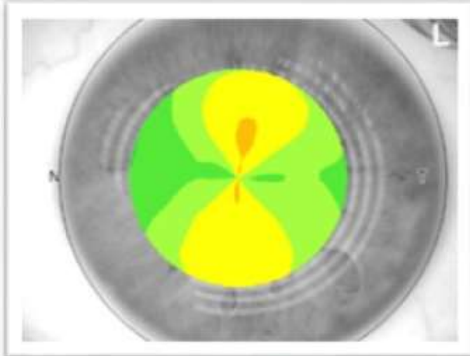
3mm

k1 = 41,96 D @ 163°
k2 = 45,31 D @ 79°
k1 = 42,19 D @ 0°
k2 = 45,27 D @ 267°



5mm

k1 = 41,90 D @ 165°
k2 = 45,33 D @ 79°
k1 = 42,24 D @ 0°
k2 = 45,12 D @ 267°



7mm

k1 = 41,65 D @ 166°
k2 = 44,99 D @ 77°
k1 = 42,21 D @ 0°
k2 = 44,93 D @ 269°

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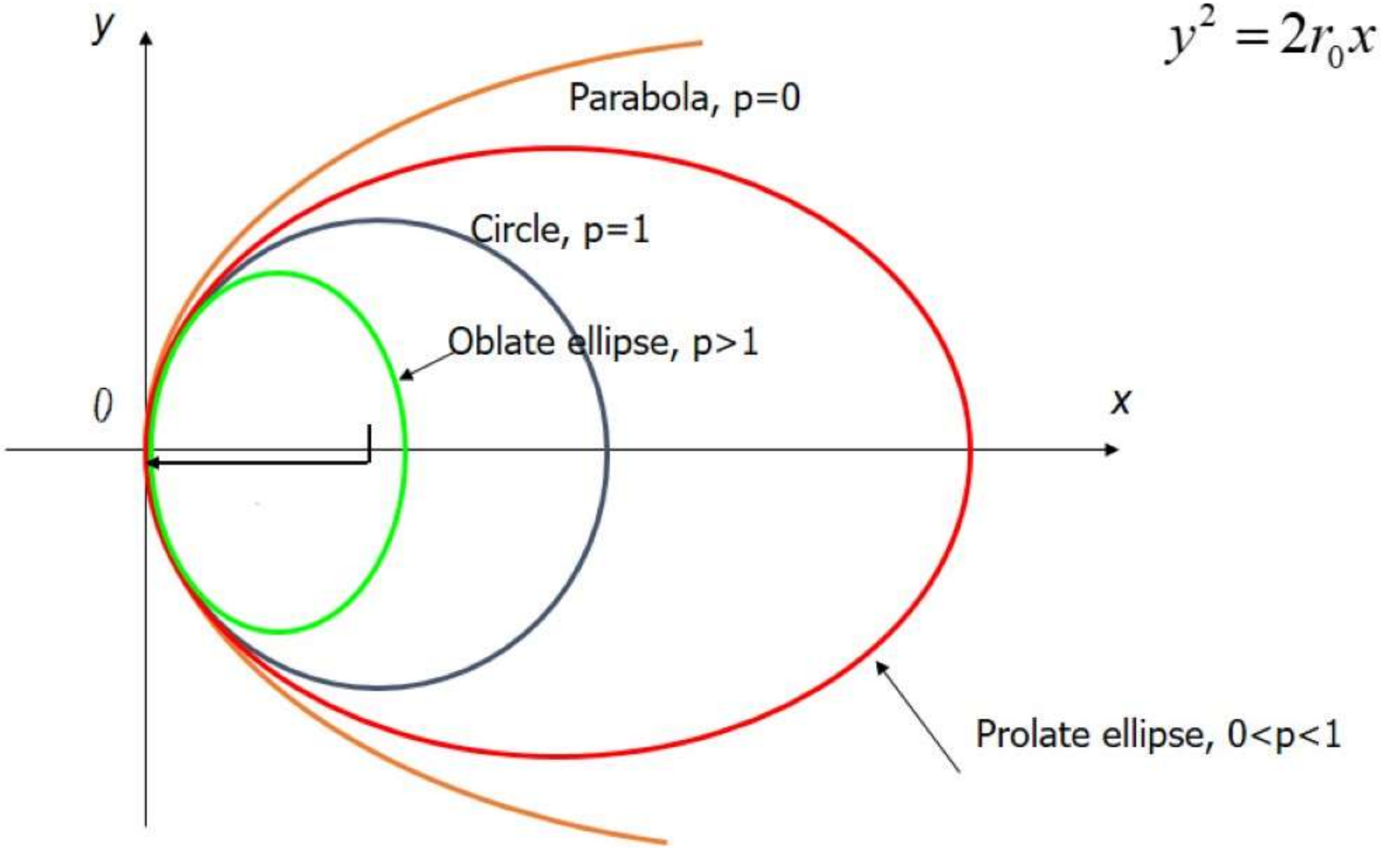
Conics

$$y^2 = 2r_0x - px^2$$

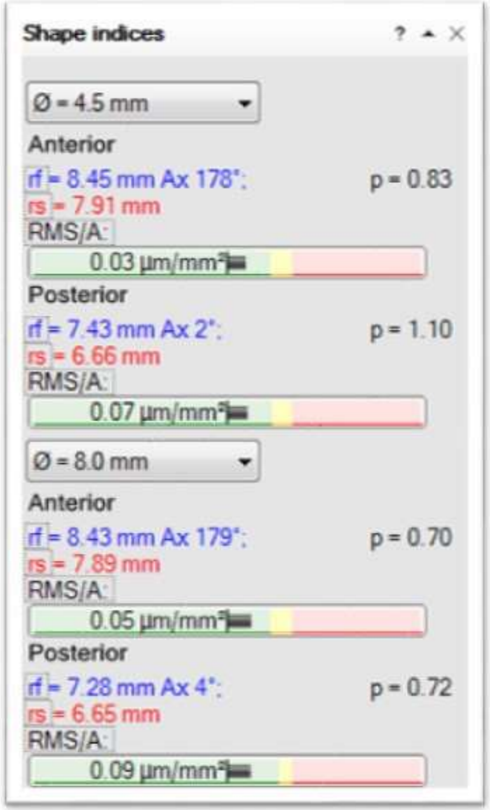


Conics

	p	Q	e	SF
p (p-factor)	-	$1+Q$	$1-e^2$	$1-SF$
Q (conic coefficient)	$p-1$	-	$-e^2$	$-SF$
e (eccentricity)	$\sqrt{1-p}$ (p<1) $-\sqrt{p-1}\ else$	$\sqrt{-Q}$	-	$\sqrt{SF}$
SF (Shape Factor)	$1-p$	$-Q$	e^2	-

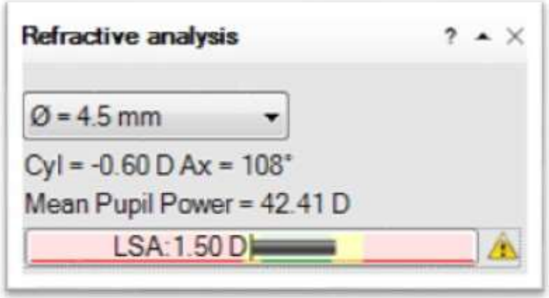
Shape indices

- Parameters rf, rs, rfAx of the best-fit asphero-toric surface for anterior and posterior surface.
- RMS and RMS/A give the difference between measured data and best-fit surface.



Refractive analysis

- Summarizes corneal refractive/optical behavior
- Pupil-dependent
- Takes in account the corneal (anterior and posterior surface) contribution to the vision;
- Based on Ray-Tracing



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Refractive analysis

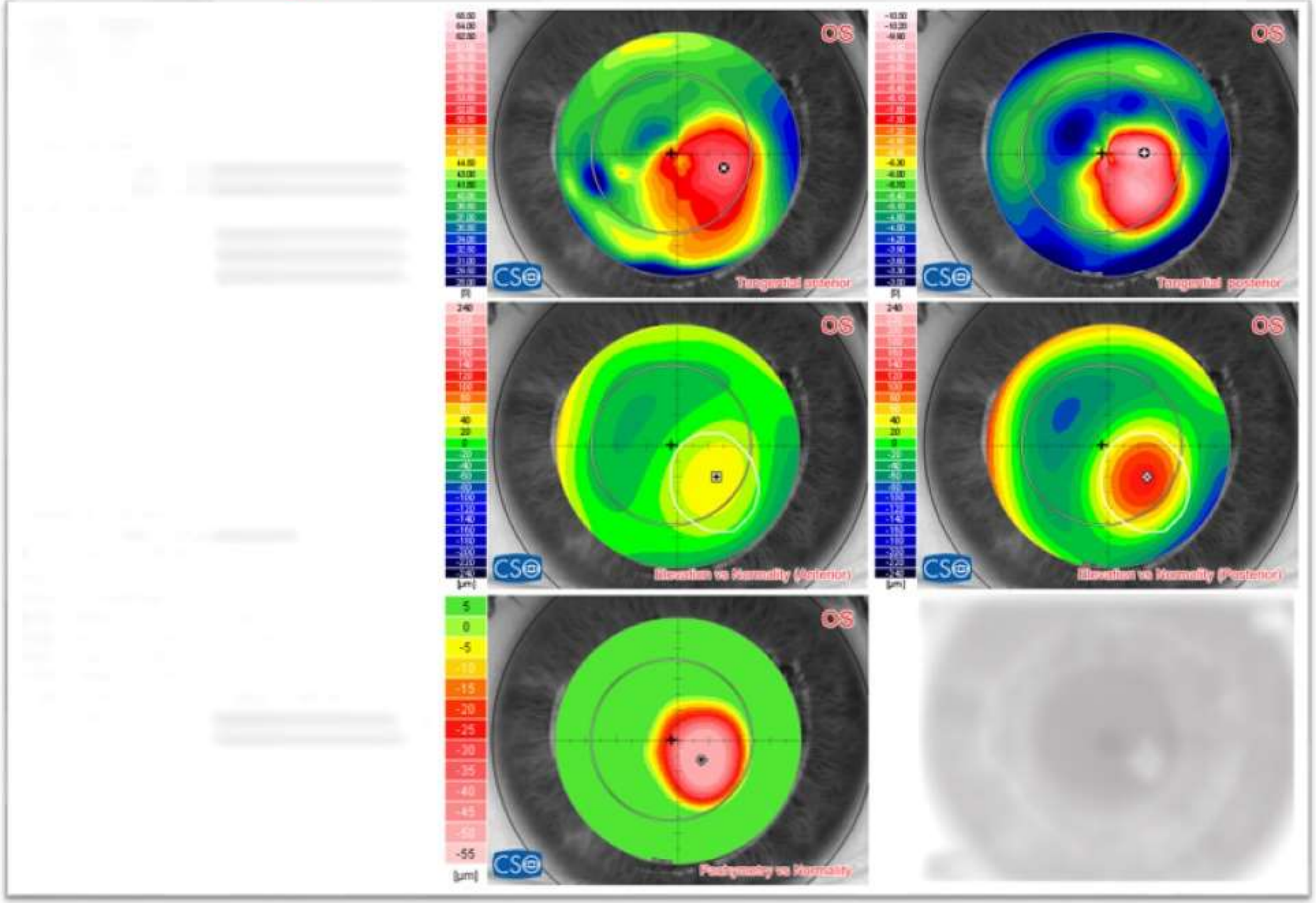
- The **Mean Pupil Power** is the equivalent corneal power (inverse of the focal length due to the cornea) expressed in D
- **Cyl** is the corneal cylinder expressed in D
- **LSA** is the corneal Longitudinal Spherical Aberration expressed in D

  - The previous indices are available for diameters of the entrance pupil ranging from 2.5 to 7 mm
  - Cyl and LSA are available also in Corneal Aberrometry Summary

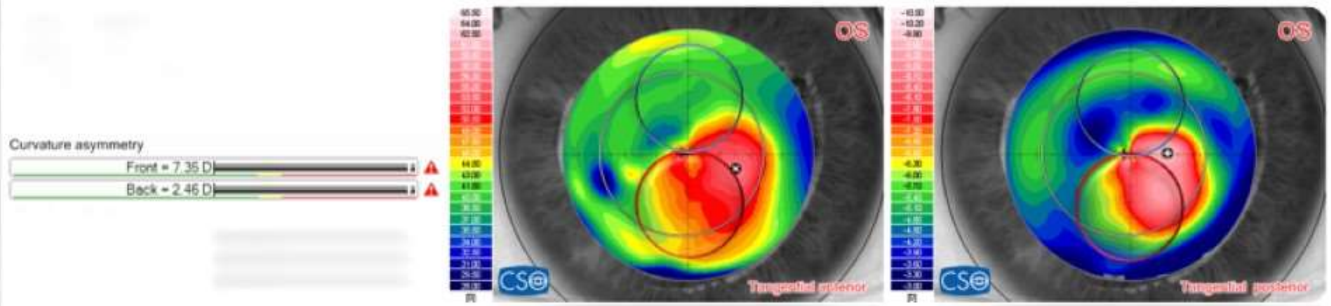
Keratoconus screening

The detection of keratoconus is a major concern in the screening of refractive surgical patients, since it is known that its presence weakens the corneal stroma and can lead to iatrogenic ectasia.

Keratoconus screening

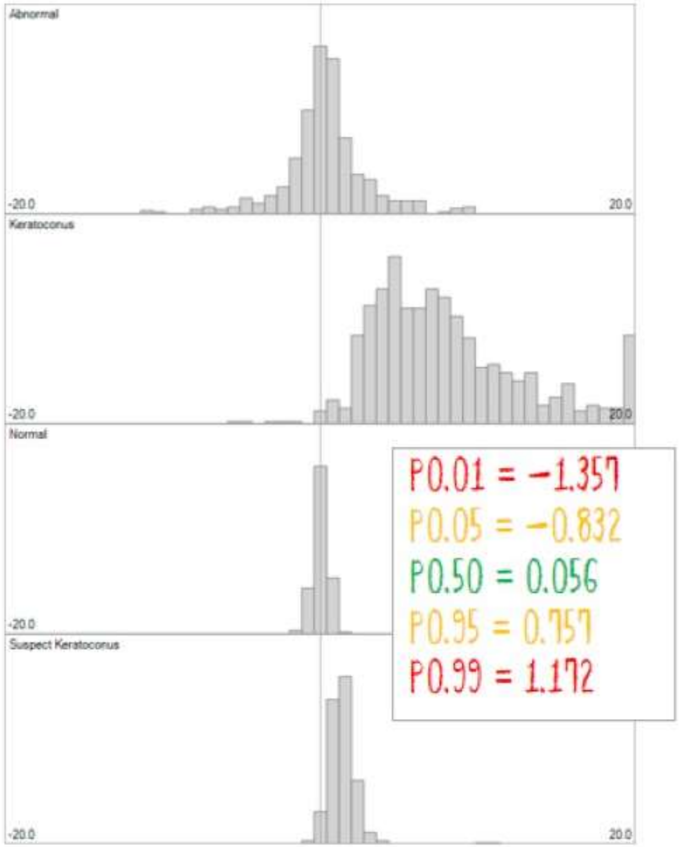


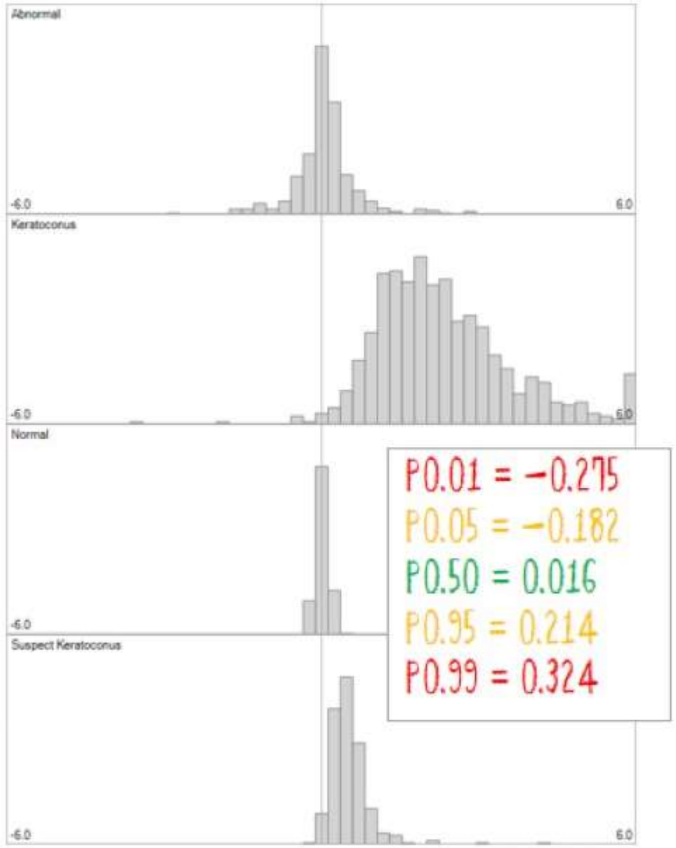
Curvature based indices



SI_f and SI_b are defined as the difference of the average tangential curvature expressed in D of two circular zones centered on the vertical axis in the inferior and superior hemi-spheres

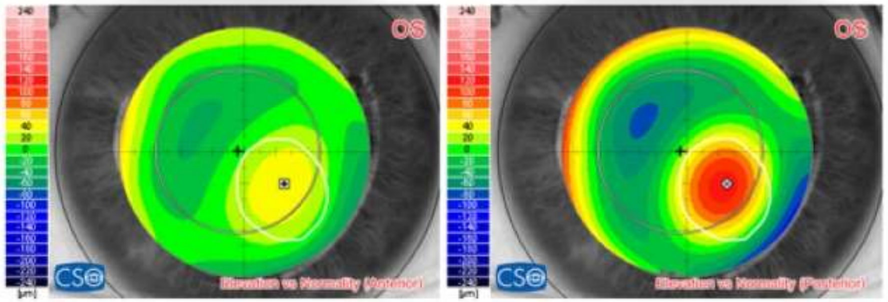
SI_f and SI_b: statistic





Elevation vs Normality

Anterior and posterior elevation respect to a best-fit reference asphero-toric surface with an asphericity equal to the average value, in the 8 mm zone, in normal eyes.



- No contribution of astigmatism and corneal mean curvature
- Emphasis of irregularities

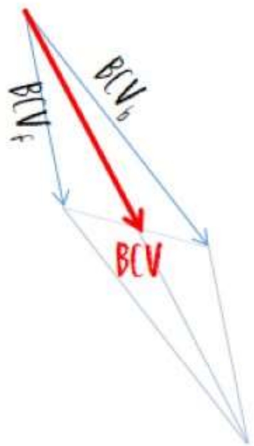
BCV_f and BCV_b

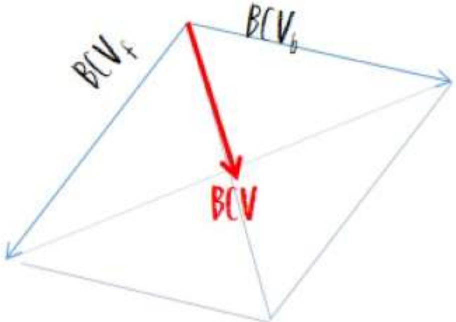
- In keratoconus ectasia statistically develops in a preferential direction (infero–temporal)
- Mainly it manifests in coma ($C_3^{\pm 1}$), trefoil ($C_3^{\pm 3}$), spherical aberration (C_4^0) components of Zernike's decomposition of elevations

- BCV_f and BCV_b are combination of the values of coma, trefoil and spherical aberration weighed by a function which fades it if the direction is not the statistically expected.

The axis of the index is defined as the value $C_3^{\pm 1}{}_{Ax}$

BCV

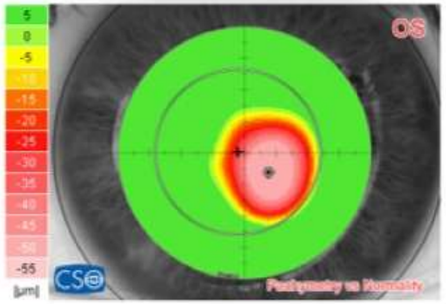




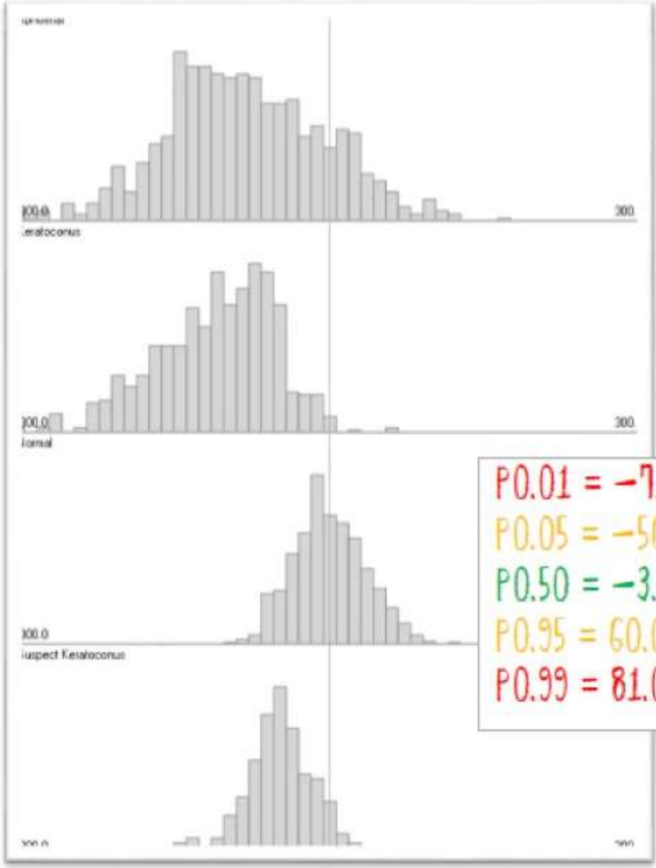
- BCV is the vectorial sum of BCV_f and BCV_b.
- In an eye with ectasia anterior and posterior corneal surfaces are morphologically similar and the directions of both the vectors BCV_f and BCV_b are correlated.
- Coincidence of the axes of BCV_f and BCV_b preserves BCV modulus.
- The diversity of the axes of BCV_f and BCV_b (in abnormal non-keratoconic eyes) produces a decrease of the modulus of BCV.

Pachymetry vs Normality map

Difference of corneal pachymetry and 2.5th percentile of the healthy population.



ThkMin: statistic



P0.01 = −71.618
P0.05 = −56.345
P0.50 = −3.609
P0.95 = 60.040
P0.99 = 81.072

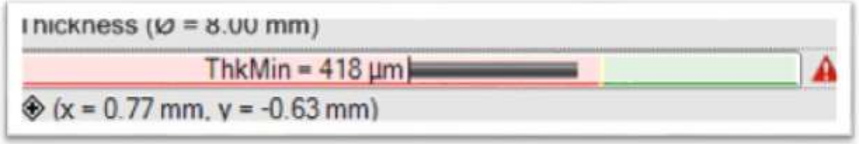


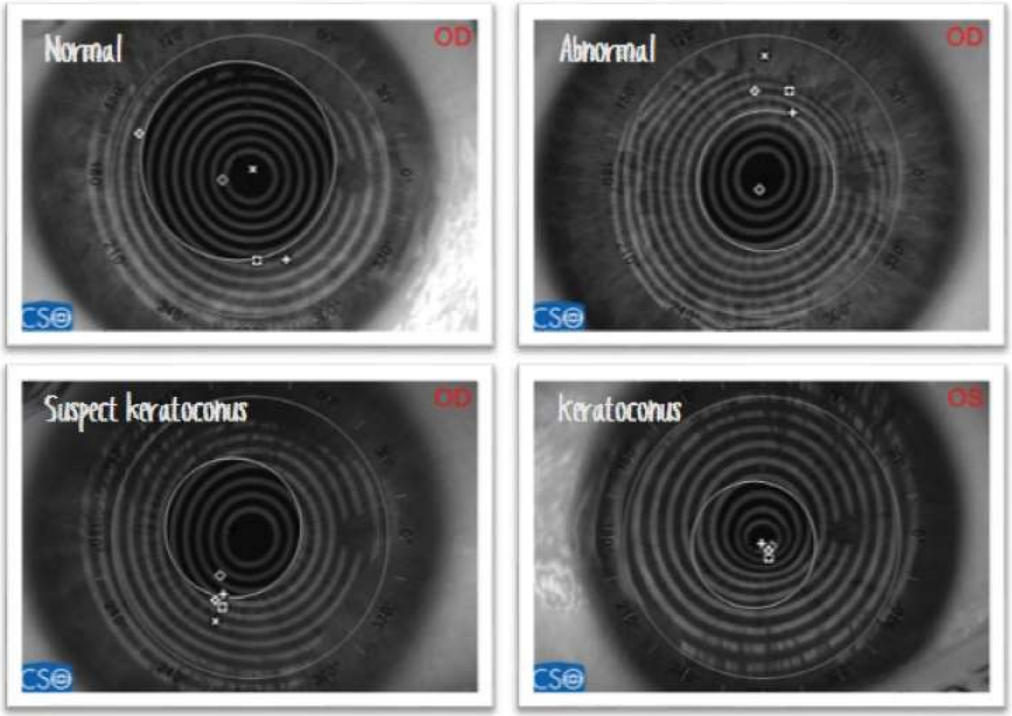
*Chart is been shifted of 540 µm to center normal group statistic in 0

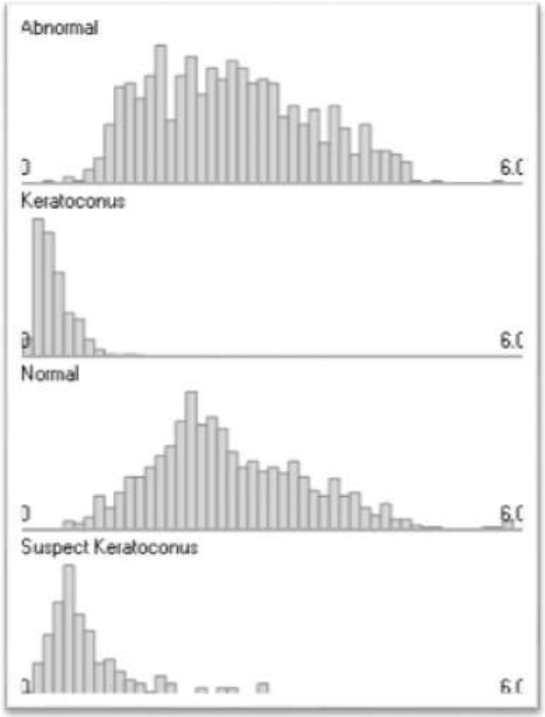
Notable points

- **Anterior Apex*** is defined as the steepest point on tangential anterior curvature map.
- **Posterior Apex*** is defined as the steepest point on tangential posterior curvature map.
- **Anterior Vertex*** is defined as the highest point of the difference between anterior corneal shape and the best-fit reference asphero-toric surface (elevation vs. normality anterior map).
- **Posterior Vertex*** is defined as the highest point of elevation vs. normality posterior map.
- **Thinnest point of cornea** defined in Pachymetry map.

*According to *Mandell RB, Chiang CS, Klein SA.* **"Location of the major corneal reference points"** *Optom Vis Sci 1995; 72:776–784*

Notable points





Results

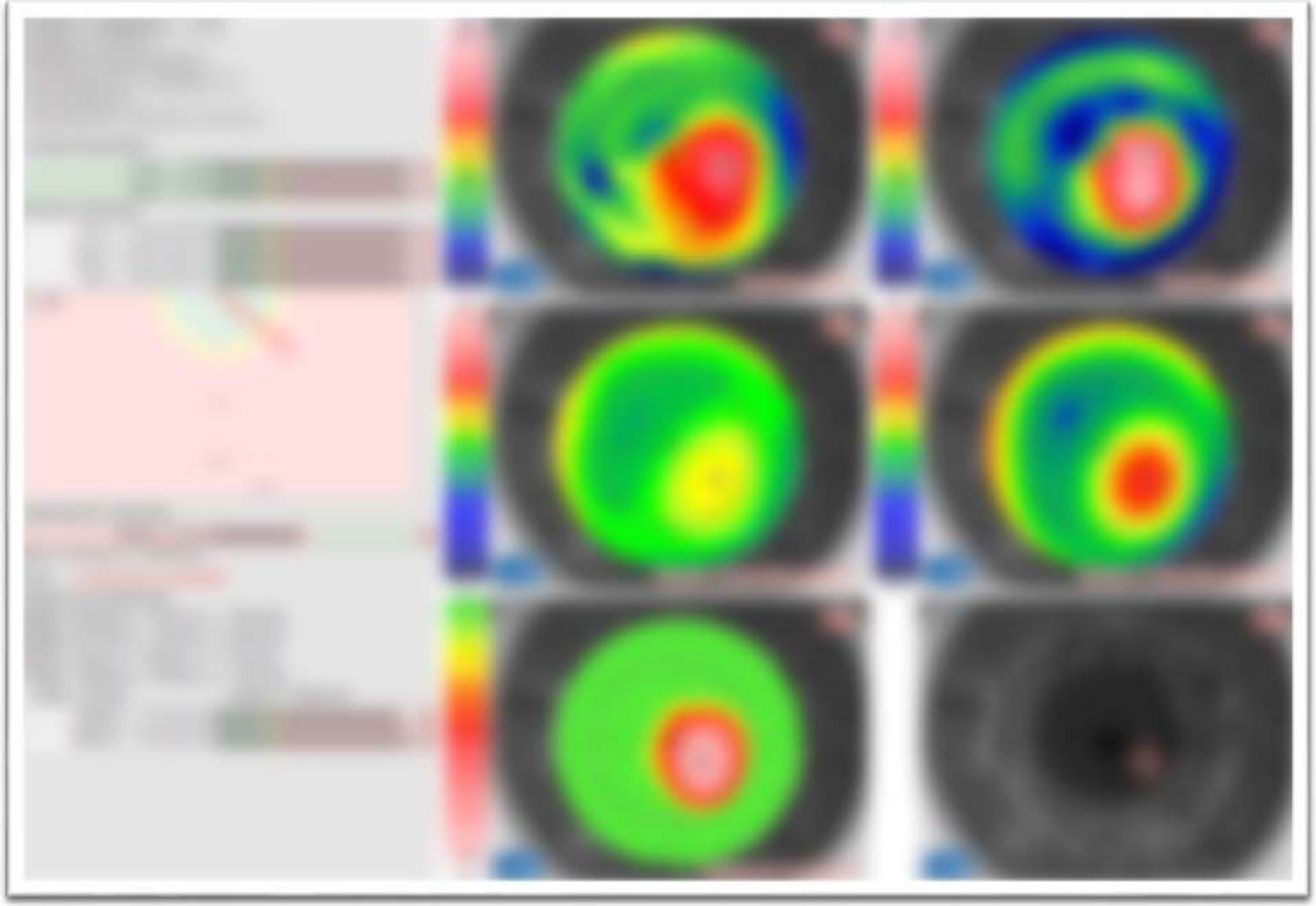
2485 eyes	Abnormal-Treated	Keratoconus	Normal	Suspect keratoconus
Abnormal-Treated (644)	96.1%	0.5%	2.0%	1.4%
Keratoconus (655)	0.6%	95.7%	0.0%	3.7%
Normal (976)	0.8%	0.0%	97.5%	1.7%
Suspect keratoconus (210)	1.4%	3.3%	1.9%	93.4%

Keratoconus screening

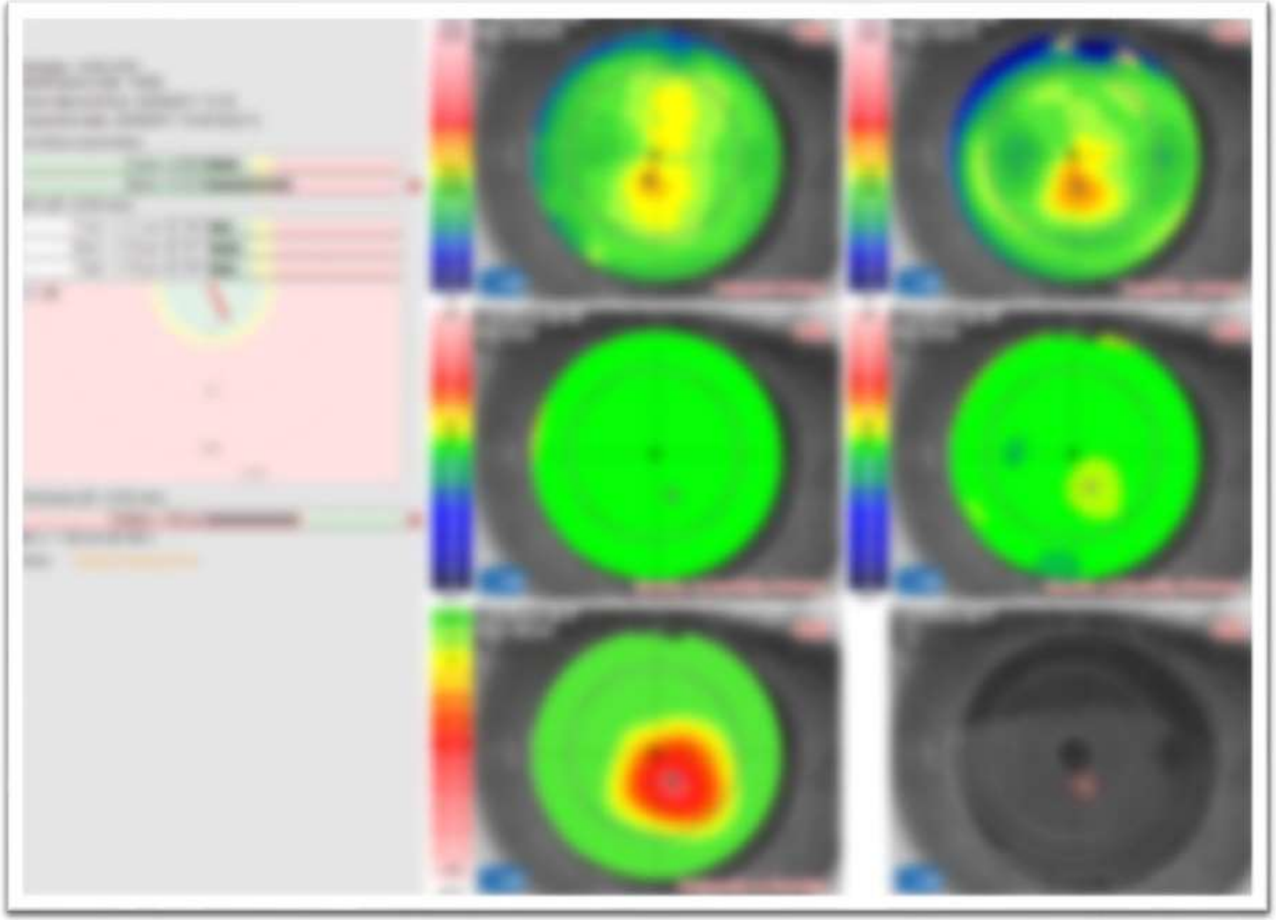
Keratoconus screening indices provide an indication based on calculated topographic information, but is not exhaustive for evaluating neither the calibration state nor the patient's clinical situation. Therefore, the mentioned indices might assist the user in formulating a diagnosis, **but are not to be considered on their own as a diagnostic interpretation of keratoconus.**

We recommend the user to use and evaluate the values presented carefully and correlate presented values with other examinations and the patient's complete clinical dossier.

Keratoconus screening



Keratoconus screening



Conventional pupillometry

A conventional pupillometer:

- measures pupil size in different light conditions
- can't link the measurement to a coordinate system (do not gives information on pupil decentering)
- Is often monocular

CSO pupillographers:

- uses visible light for the stimulus and IR for capturing
- measures pupil size in different light conditions:
  - Scotopic light condition (0.04 lux)
  - Mesopic light condition (4 lux)
  - Photopic light condition(50 lux)
  - Dynamic (starting from 200 lux and switching off the Placido illuminance)
- links the measurement to the map
- uses binocular photo stimulus (both the eyes perceive the same illuminance)