

Principles and Clinical Applications of Ray-Tracing aberrometry (Part I)

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ABSTRACT: The visual quality of the eye depends on several optical and neural factors. In the nineteenth century, Helmholtz found optical errors that could not be corrected using existing optical theory. In the process of image formation in the human eye there are three major sources of degradation: A) Diffraction B) Scattering and c) Optical Aberration. Optical aberrations are the most important source of impairment of the quality of the optical system. The definition of an optical aberration is a departure of the performance of an optical system from the predictions of paraxial optics. In an imaging system, it occurs when light from one point of an object does not converge into (or does not diverge from) a single point after transmission through the system. Aberrometers are currently the most important tools for estimating optical conditions so that a more complete understanding of optical error can be quantified and corrected. A variety of principles are used, such as Hartmann-Shack, Tscherning, Ray Tracing and automatic retinoscopy. Aberrometry presents diagnostic and therapeutic applications. We can determine the visual quality and objectively interpret the eye's ability to resolve spatial frequency and contrast sensitivity. At other times analyze refractions on a multi-zone basis, assess aberropia in the most complex cases (corneal transplants, irregular corneas, cataracts ..) that cannot be measured with other devices. Aberrometry can also be applied in therapeutics goals such as wavefront-guided treatments, designing lenses to compensate optical aberrations or Adaptive Optics. In this review we analyze the Ray-tracing aberrometry and its application to daily clinical practice. The ray tracing principle is a serial, double-pass method using forward projection that can be implemented in both an objective and subjective manner. By integrating corneal topography with wavefront aberrometry, the iTrace provides a unique analysis that subtracts corneal from total aberrations in order to isolate the internal aberrations of the eye. It also can measure accommodation with a near-point refraction feature.

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INTRODUCTION TO THE iTRACE SYSTEM

The iTrace System (Tracey Technologies, Houston, Tx) is uniquely designed to combine Placido corneal topography with a ray tracing aberrometer to measure quality of vision in a patient¹. The adaptation of the

Ray Tracing technology to ophthalmology is due to the research developed by Vasyl Molebny and a team of engineers in Kiev (Ukraine)². Ioannis Pallikaris, ophthalmologist, was also involved in developing the equipment^{3,4}. The result is an instrument able to measure total aberrations. A topographer was added to this aberrometer to measure corneal aberrations, this allows

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Figure 1. The iTrace measuring system. The latest configuration of the instrument allows aberrometric and topography measurements in the same «measurement axis» for a more real and detailed analysis of the whole ophthalmic optics.

us to analyse the whole visual system section by section. Since its inception, there have been several updates both in its hardware and in its software (Tracey-1, i-Trace). In the last version the topographer and the aberrometer are not separated, they can be found in the same unit (iTrace Combo Visual Function Analyzer, Software Version 4.2) (fig. 1).

RAY TRACING ABERROMETRY

Ray tracing concept

Aberrometry based on the principle of Ray Tracing is, a two-step, serial technique that uses forward projection and which can be used either subjectively or objectively⁵.

The ray tracing method uses a laser beam parallel to the line of sight through the pupil. It measures the exact location where the laser beam reaches the retina by means of the retro-reflected light captured by reference lineal sensors X, Y. Local aberrations in the path of the laser beam through the cornea and the internal structures cause a shift in the location on the retina. Once the position 1 has been determined the laser beam is shifted to another position, which is then located in the retina. This process continues until several separated points are projected into the entrance pupil. This way a connection is obtained between the direction that the light beams have taken while entering and leaving, allowing a reconstruction of the real wavefront error. This principle measures «forward» aberrations of the light that goes through the eye. It is more physiological to measure these anterior aberrations as the natural trajectory of the light in the eye is analysed.

Several laboratory experimental aberrometers based on Ray Tracing, such as those from Navarro and Barriuso, have been described in literature⁶. The only aberrometer that is commercialised for clinical use is the iTrace (Tracey Technologies, Houston, Tx). The iTrace uses this fundamental principle of Ray Tracing where a sequential series of infrared beams on the order of 100 microns and a 785 nm wavelength each is projected into the entrance pupil parallel to the eye's line of sight. In Figure 2, a diagram of the Ray Tracing technique developed by Tracey Technologies is shown.

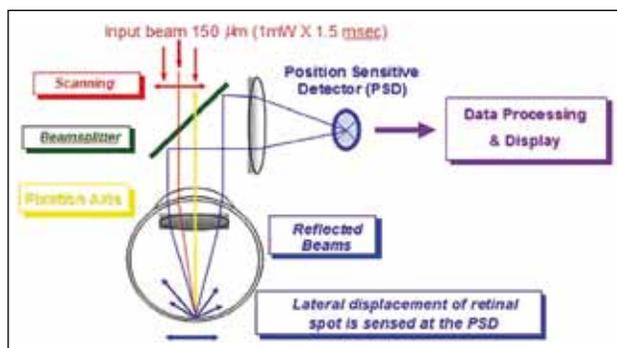


Figure 2. Diagram of the Ray Tracing technique.

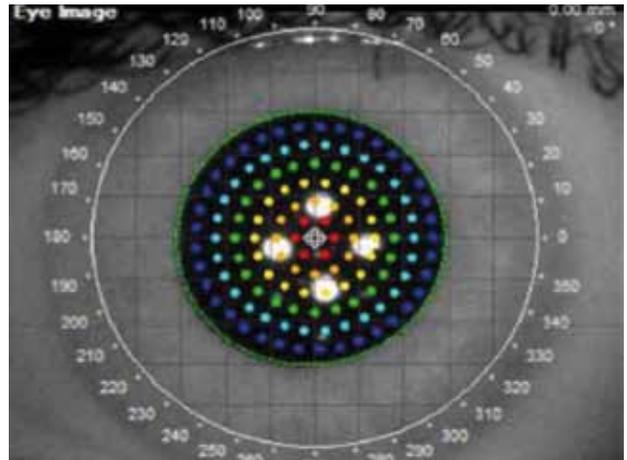


Figure 3. iTrace projection pattern. 64 thin, parallel light beams are projected through the pupil. A forward aberration measurement is made.

Once the position of point 1 has been determined the laser beam is shifted to another position, and the localisation of the next point in the retina is registered. This process continues until 64 laser beams have been projected through the entrance pupil 4 times each (256 points) at high speed (approximately 250 milliseconds). Each of these points represents the entrance of parallel light rays into the eye, which become refracted by the eye's optical power and eventually focus on the retina. If the eye were emmetropic, all 256 points would be concentrated at a single point in the centre of the macula. In other words, the fovea is represented by the conjugate focal point of the system. Generally, local aberrations at the beam's entry point on the cornea or the lens cause a shift in the location on the retina with respect to a position of reference. The advantage of Ray Tracing over other aberrometric principles is that the scanner x-y can be programmed to analyse any other rectilinear or polar patterns. The iTrace uses a pattern of concentric rings (fig. 3).

Retinal Spot Diagram (RSD) Concept. Obtaining PSF and MTF

When a set of points is sequentially projected in the entrance pupil a retinal spot diagram (RSD) is created. The RSD contains all the information related to the patient's refraction, aberrations and point spread function (PSF). Analysing the RSD's morphology, we get an idea of the degree of the wavefront's qualitative aberration (fig. 4). The smaller the RSD the higher the concentration of photons that reaches any point of the retina.

From the RSD we obtain the PSF (Point Spread Function). PSF shows the image obtained in the retina when the patient sees the source of a point of light. The smaller and the sharper the better. Likewise, from the RSD the wavefront deformation (aberrometry) and the MTF (Modulation Transfer Function) maps can be calculated (fig. 5). The MTF describes how the optical system repro-

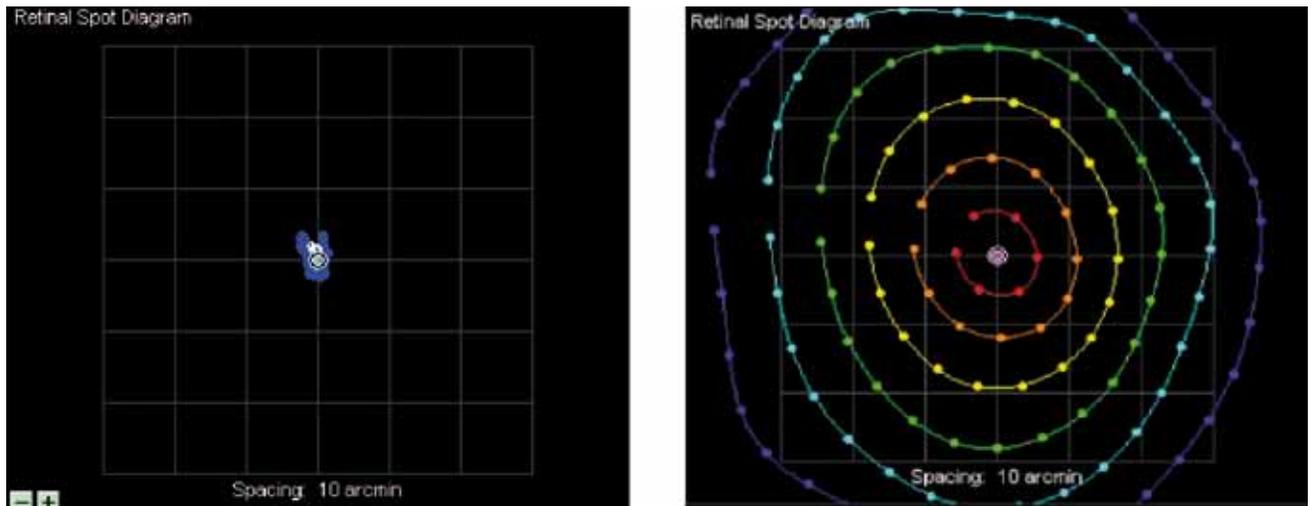


Figure 4. Image of the RSD of an emmetropic patient (left) and another myopic patient -5.00 dp (right). It may be observed that in the myopic eye, the most important aberration is defocus.

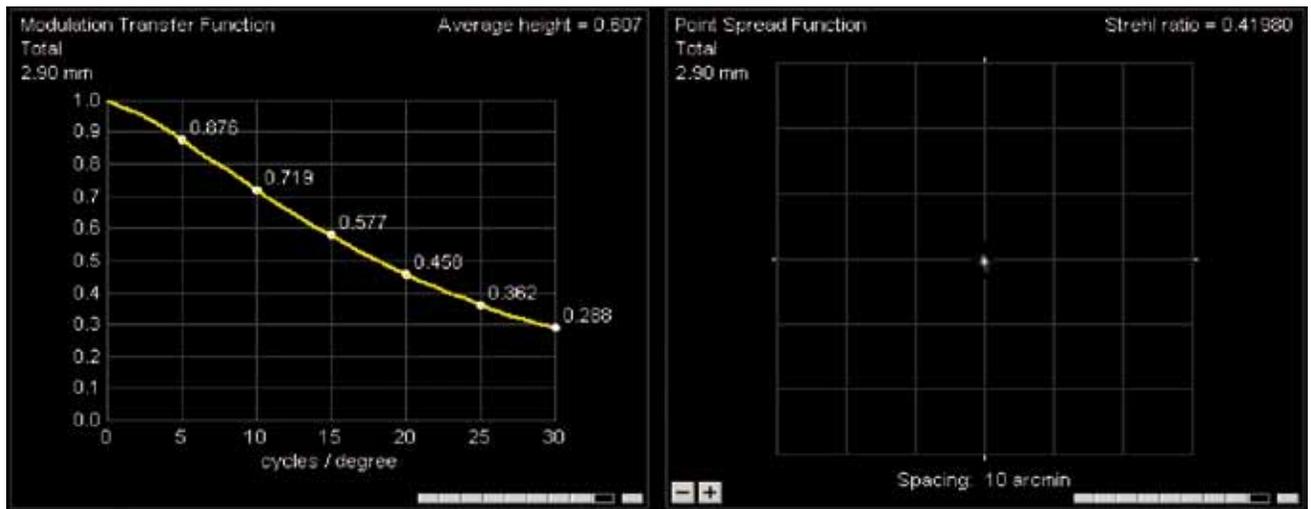


Figure 5. MTF and PSF Total of an emmetropic patient with good visual function.

duces detail from the object to the image produced by the lens; therefore, both the MTF and PSF help to describe the optical system’s ability.

TECHNICAL DESCRIPTION OF iTRACE VERSION 4.2

The data acquisition unit (DAU) is the main component of the iTrace (fig. 1). The DAU is used to project the laser beams to the retina and to subsequently process them with its software. The DAU has an adjustable focus

Table 1. Specifications of the i-Trace System
Measurement range: ± 15 D sphere ± 10 D cylinder
Size of measured pupil: 2.5 mm to 8 mm
Accuracy: ± 0.10 D
Reproducibility: ± 0.10 D

target, a pupil size detector and an internal optometer. The optometer is the fixation equipment, which aligns a patient’s line of sight to the laser’s axis. It is also used to relax the accommodation of the patient («fogging») adding an increase/decrease lens of spherical correction (range $+7$ D to -5 D). The DAU is completed with a corneal topographic analyser such as Placido. The iTrace’s technical characteristics are summarised on Table 1.

INITIAL MEASUREMENTS WITH THE i-TRACE

Verifying the quality of the measurement in the wavefront exam. Point profiles

The WF Verification Display shows all the patient’s data on limbal diameter, pupil size and scan diameter (fig. 6). The iTrace takes the measurement on the real pupil of the patient with a range of pupil size between

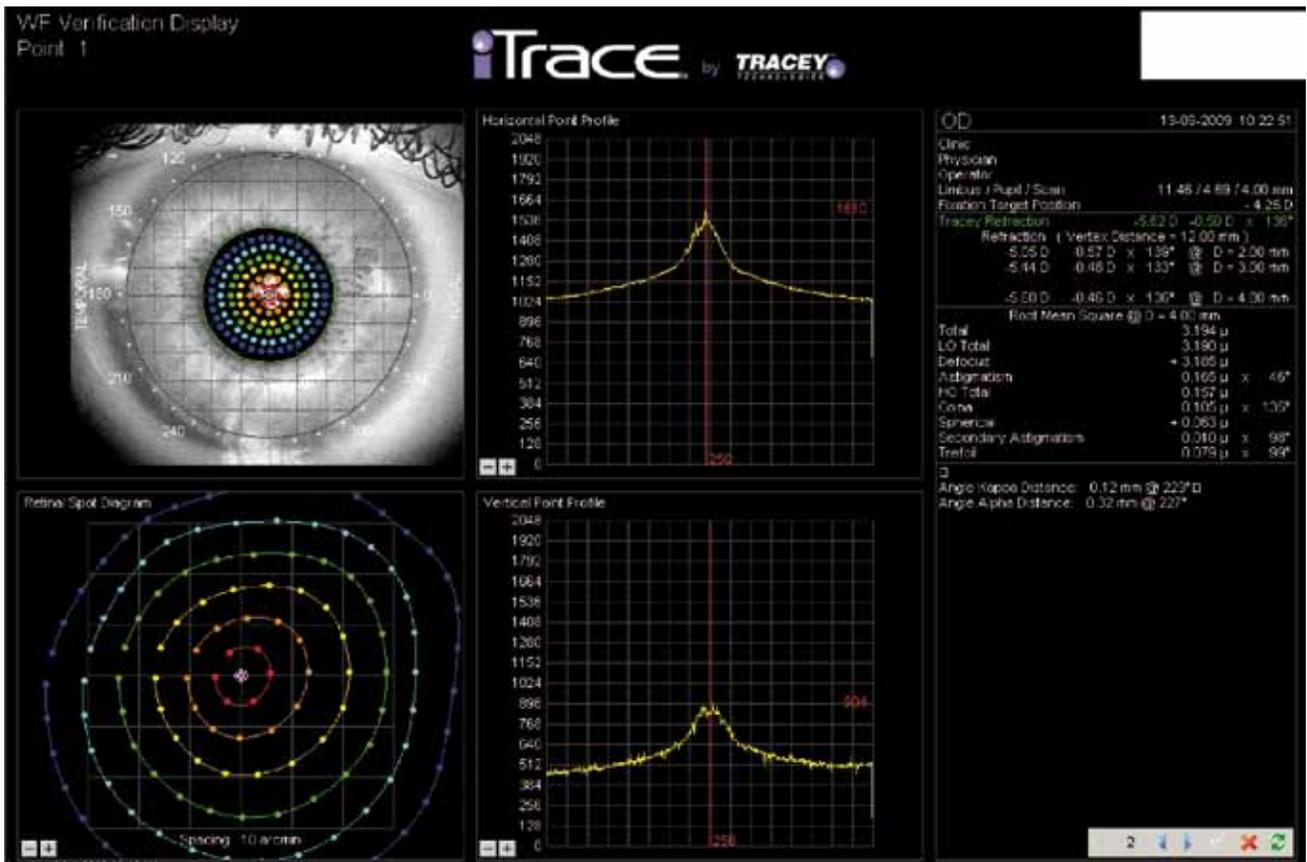


Figure 6. Overview screen of the WF Verification Display. The RSD is on the bottom left corner and the two point profiles (horizontal and vertical) that express the quality of the measurement are in the centre.

2.5 and 8.0 mm, as shown in Table 1. The examiner can also select manually the analysed pupil diameter to determine where certain aberrations occur and how do they affect vision.

The ability to display the colour map of the entrance pupil, where each point is colour-coded depending on the refractive correction required in that point, is of great use when the examiner is assessing the visual function of the patient.

This screen (fig. 6) shows the number of non-measured or rejected points. If they are less than nine they are displayed in yellow and if they are more than nine they appear in red and the exam is invalid. Occasionally, those unmeasured points are due to an opacification (corneal scar or cataract).

In the centre of this screen (fig. 6), we find two diagrams that verify the signals, the Horizontal Point Profile and the Vertical Point Profile. These diagrams show the position of each point that reflects on the retina, taking the centre of each profile in the X and Y-axis. It gives us an image of the quality of the laser's signal captured in our measurement; if the profile is irregular the measurement is incorrect.

The Retinal Spot Diagram (RSD) is also shown in this screen. The RSD concept has already been explained. If the RSD is too distorted it indicates an error in the measurement or an eye with many aberrations (fig. 7).

Refraction measurement with the iTrace

The iTrace is also an autorefractometer. By means of this function conventional refractive indexes (sphere and cylinder) are obtained through calculations based on the Zernike coefficients. This way different refractive values, depending on the size of the pupil area analysed (Multi-zone refraction analysis), are obtained (fig. 8).

The value displayed in green (Tracey Refraction Number) (fig. 8) is obtained from the measurement at 4 mm or the greatest measurement if the pupil is less than 4 mm. Below the Tracey Refraction Number is the multi-zone analysis. The smaller the HOA, the more homogeneous is the multi-zone refraction analysis in the different optic zones. Likewise, the iTrace uses an open-field to minimise the patient's accommodation. A study in 69 eyes has demonstrated a high concordance ($T = 0.9925$) between the manifest refractive power and the one measured by the iTrace⁷ (ranges from -0.01 to -0.4 D). This study was carried out with a range of spherical equivalent refraction of -13 D to $+7$ D (the iTrace measurement range is of -15 D to $+10$ D). This study concludes that the refraction of the iTrace is more accurate than that of the WaveScan (Hartmann-Shack aberrometer) in eyes that have undergone corneal refractive surgery⁷.

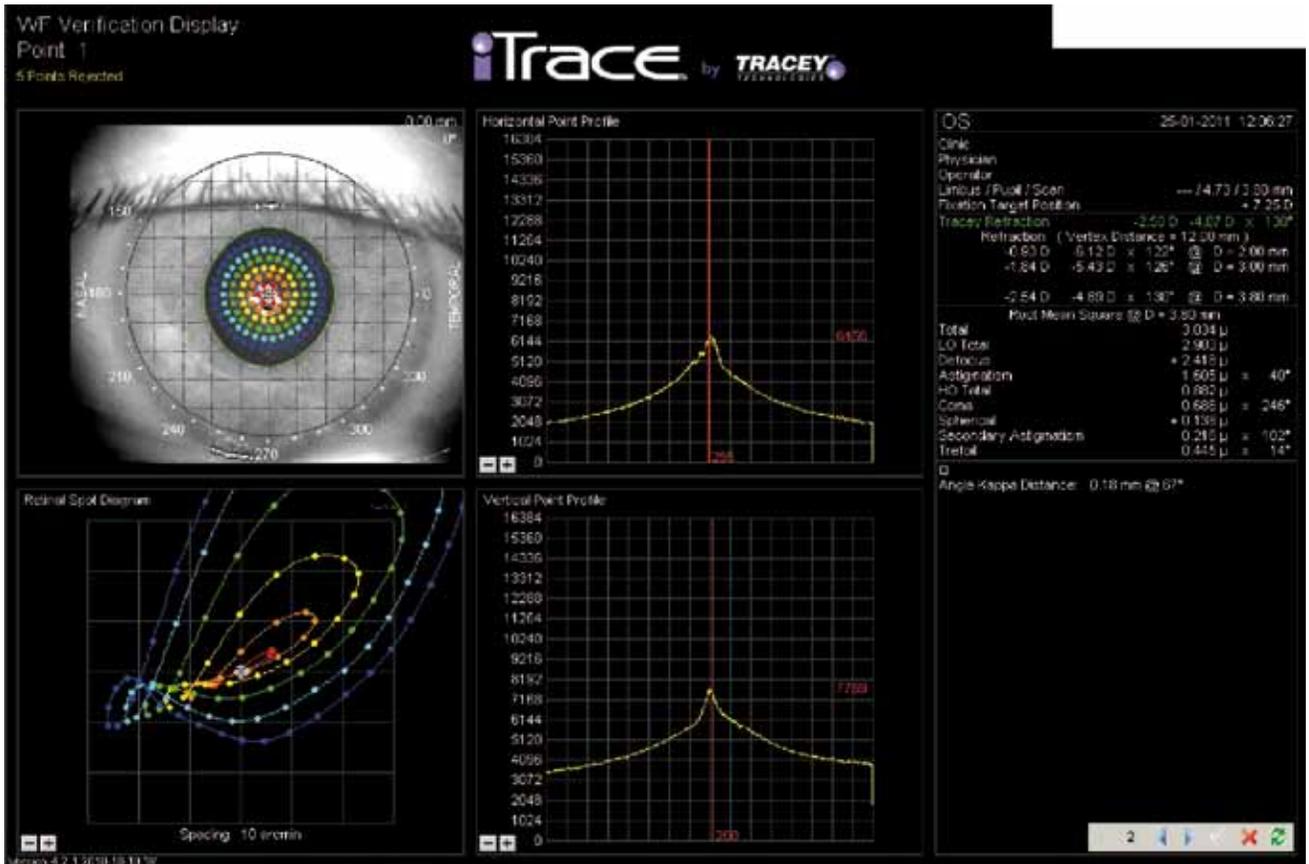


Figure 7. WF Verification Display of a keratoconic eye. The RSD is very distorted due to the amount of altered aberrations. In the centre, the horizontal and vertical point profiles show a good measurement in spite of the corneal irregularity.

Another comparative study of the refraction measurements of 6 aberrometers (iTrace, OPD-Scan, Zywave, WASCA, Multi-Spot Hartmann and Tscherning) observed that spherical and cylinder values are 0.2 D greater in the iTrace than in the rest of the aberrometers⁸.

pear afterwards in the different «screens» or «display». The description «Total» indicates that the graph includes all high-order and low-order aberrations (HOA and LOA), while «HOA» indicates that the graph only shows high-order aberrations.

BASIC DATA GRAPHS WITH THE i-TRACE

The iTrace shows its differently processed data. There are 6 basic kinds of graphs, their descriptions are stated below. Combinations of these 6 basic kinds ap-



Figure 8. Multi-zone refraction analysis based on aberrometric data. Its values depend on the different pupil diameters analysed.

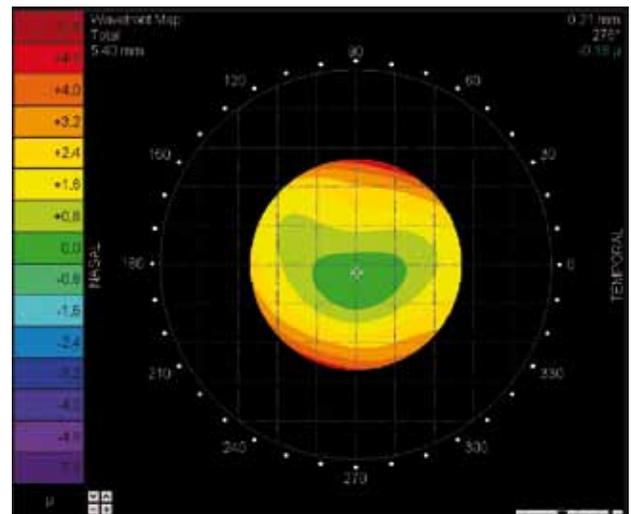


Figure 9. Wavefront Map Total. Shows all the aberrations of the eye. Green areas indicate little or no aberrometric error (there are 0.18 microns in the centre), while warmer-coloured areas (in this case, in the periphery) indicate an advanced aberrometric error.



Figure 10. Total RMS values, Total LOA and Total HOA (bottom right) and decomposition in each of the Zernike polynomials represented in red and blue bars depending on the value of the sign.

– **Wavefront map Total and High-order Aberrations (HOA) (Wavefront Total and Wavefront HOA).** These maps show colour-coded wavefront aberrations of the eye measured in microns of error (fig. 9). The error can be positive or negative. Measurements are taken from the entrance pupil.

Warm colours indicate that the wavefront is in front of the reference plane and blue colours indicate that the wavefront is retarded in relation to this plane. A very useful function is to determine what kind of aberration, if any, is controlling the refractive errors of the eye. Most common high-order aberrations (HOA) are:

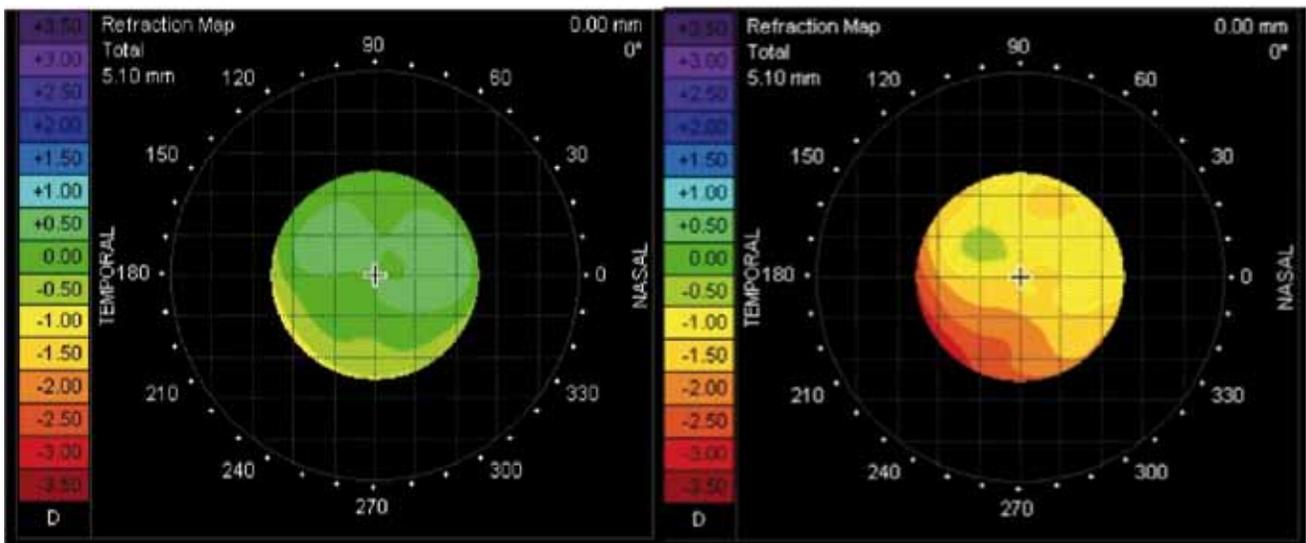


Figure 11. Refractive map of a patient with mild hypermetropia and astigmatism (+0.52 -0.37x152°) (left) and Refractive map of a myopic patient (-1.12 -0.50 x148°) (right).

coma, spherical aberration, high-order astigmatism and trefoil.

– The **RMS (Root Mean Square)** is the measurement of the magnitude of the aberration. A total RMS value for the total aberration of the eye and a specific value of RMS for each Zernike term or component of the eye aberrations can be obtained (fig. 10).

– **Total refractive and HOA refractive maps.** These maps show the refractive power of the eye in dioptres. These measurements refer to the whole eye and not only to the corneal power. Emmetropia is represented in green. Myopia in red and hypermetropia in blue (fig. 11). This map in combination with the topographic one can indicate if the astigmatism is purely corneal or if it has a lenticular component. The objective measurement of accommodation is done comparing these maps taken at different distances and analysing the refractive change (see accommodation measurement section).

– **PSF Total and HOA PSF. PSF (Point Spread Function)** is a figure of merit representing the quality of the image of an optic system, determined by the aberrations to a simple point of light. The more aberrations, the higher the defocus effect obtained (fig. 12). The PSF is used to calculate the Encircled Energy Function and to determine the maximum PSF.

– **Snellen Letter Total and high-order aberrations (HOA).** The Snellen Letter («E») is a simulation

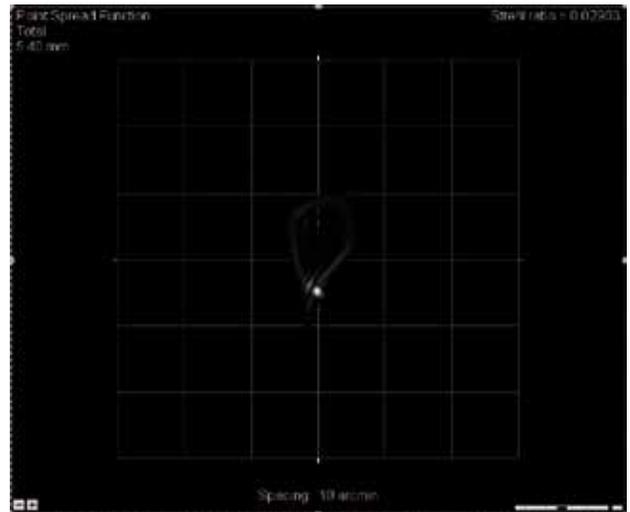


Figure 12. PSF Total of a myopic patient after a decentration treatment of ortho-k. The typical shape of the coma-like aberration induced by the decentration of the contact lens can be seen.

of the iTrace system based on an estimate mathematically derived (convolution) from how the eye «would see» the letter «E» projected in different sizes such as 20/20, 20/40, 20/100 and 20/200. This «virtual optotype» allows the examiner to see «what the patient sees» and to clinically determine the visual discomforts reported by the patient (fig. 13).

– **Zernike polynomials.** It is a bar graph and a table of the terms or polynomials of Zernike, which

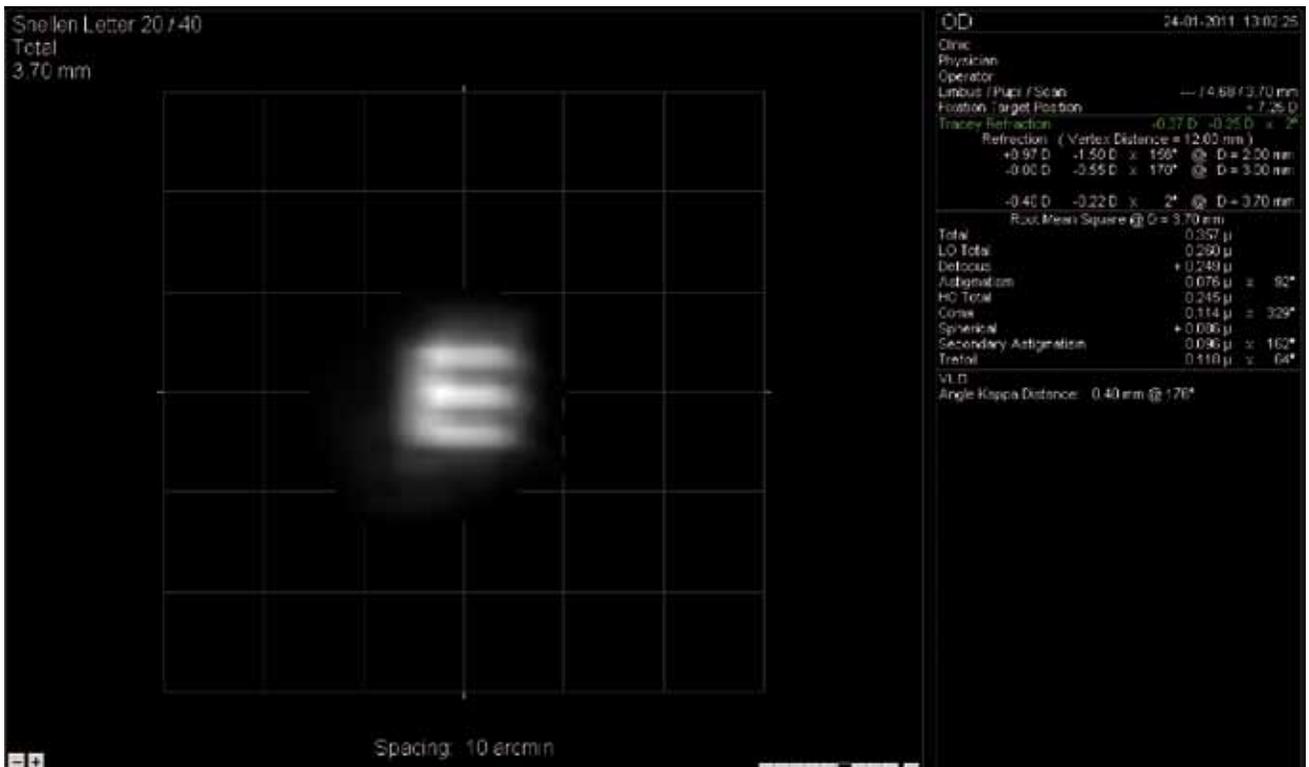


Figure 13. Snellen Letter Total of a patient after implantation of a diffractive multifocal IOC. Despite low spherocylindrical refraction (−0.37 −0.25x2°), reports halos and glare mainly in scotopic conditions.

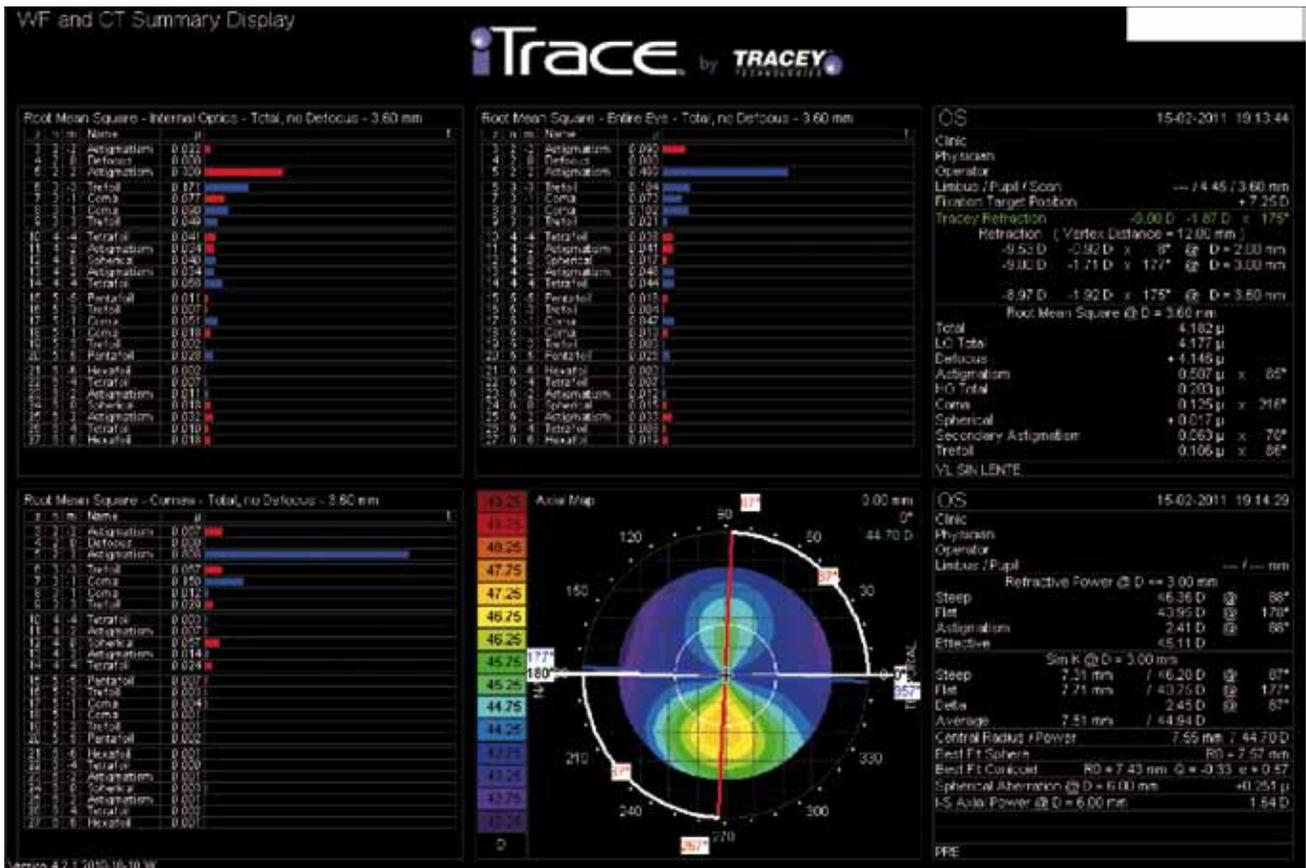


Figure 14. Bar graph of the Zernike polynomials (up to the 6th order) of the entire optic. A 58-year-old patient with high myopia in whom the high burden of corneal astigmatism is observed (Z 2,2) (blue bar, bottom left).

show a detailed analysis of the specific aberrations in an eye. The iTrace shows the Zernike polynomials up to the 6th order (27 terms) and can show the totals for the eye («Total»), only the corneal and the difference between the corneal and the totals (internal optics) (fig. 14).

– Aberration of internal optics analysis. Wavefront combined analysis and corneal topography.

This graph provides us with very valuable information unique to the iTrace system. Through corneal topography the corneal aberrations map can be mathematically generated and these aberrations can be adequately subtracted from the total aberrations of the entire eye (fig. 15). The resulting difference obtained by subtracting the corneal aberrations from the total aberrations mainly represents the aberrations of the internal optics; in this way aberrations from the cornea can be separated from those from the interior of the eye. Most of the aberrations of the internal optics are induced by the crystalline. From a clinical point of view this can help us in certain situations:

- If a patient has high total aberrations we can know if the refractive procedure we are planning is better in the cornea or in the crystalline.
- If a patient has undergone a phacolensectomy we study the aberrations (induced or compensated) intro-

duced by the IOL with a map before and after (analysing the aberrations of the internal optics, cornea and total) (fig. 15).

- Different types of IOL can also be analysed.
- We can analyse in an opacified crystalline how many aberrations it is inducing in the total of the eye.

DATA REPRESENTATION. DATA ANALYSIS SCREENS

With the iTrace system we can analyse topographic and aberrometric data. These data will be reflected in different screens or Displays.

Wavefront analysis

It is done through two displays:

a) Visual Function Analysis (VFA Summary Display) shows the Refraction Map HO Total or the Wavefront HO Total (depending on which one we select). Refraction in different diameters, the RMS, PSF, Snellen letter and Potential Visual Complaints (nocturnal myopia, halos, glare, defocus, double vision). These symptoms are quantified with 1 to 3 crosses depending on their intensity and they are marked in red or yellow.

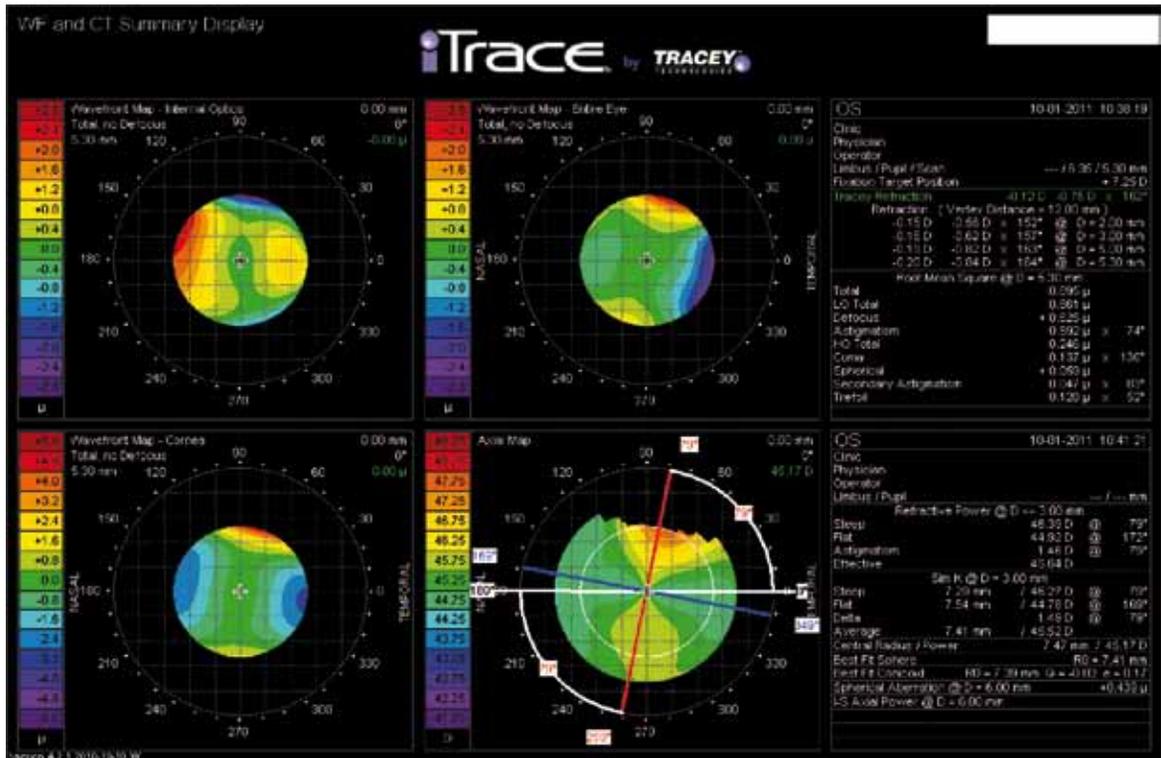


Figure 15. Analysis of the entire optics of the eye, through the Wavefront map Total (top right), corneal wavefront (bottom left), wavefront internal optics (top left) and the topographic map (bottom right). In this case we are analysing a patient with a toric diffractive multifocal IOL with a negative spherical aberration. Studying each map we can see that there is a with-the-rule corneal astigmatism, which gives rise to an astigmatic corneal aberrometric pattern. A large proportion of this astigmatism is compensated by the IOL, giving rise to a more uniform total aberrometric map (green colour) although with a mild astigmatism manifested in the Tracey refraction. On top of this, the corneal spherical aberration (Z 4,0) is being cancelled by the IOL (due to its aspheric design) and the total spherical aberration is close to 0.

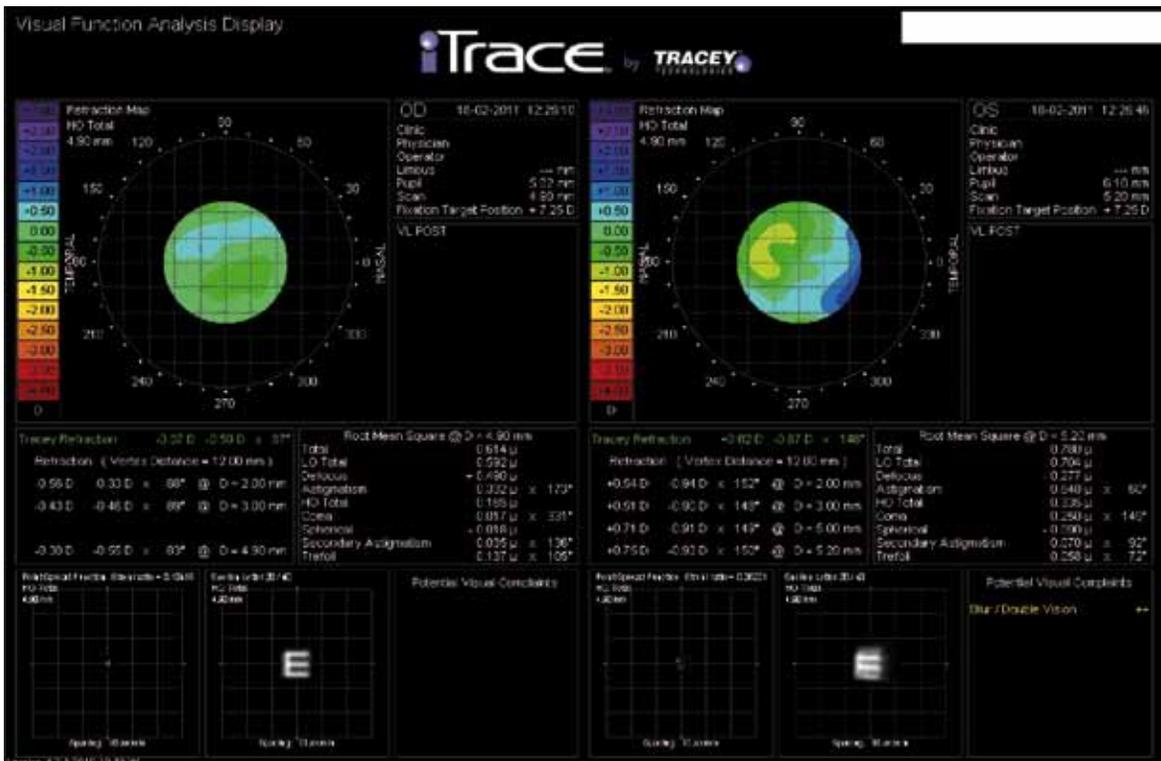


Figure 16. Visual Function Analysis of a patient who has undergone Lasik refractive surgery. Monocular subjective VA is 20/20 although the patient reports a higher distortion in the LE; this is confirmed with this analysis.



Figure 17. Wavefront Comparison Map Total of a patient who has undergone Lasik refractive surgery. The bottom Wavefront Map (Post Lasik) shows how total aberrations have improved (mainly the defocus), as the map is almost all green (0.0 microns) and to the left, the difference map.

low depending on their grade. There is a pupil diameter regulator at the bottom, which can be used to change the study size of the entrance pupil (fig. 16).

b) Wavefront comparison map. It compares two wavefront maps in one patient. This map has *two* important uses: a) When the patient undergoes any refractive procedure and we want to compare the status of the aberrations before and after the surgery. B) Its other use is to measure the accommodation; this is explained in the corresponding section (fig. 17).

Corneal Topographic Analysis (CT Summary Display)

See the iTrace Topographic System section.

Wavefront (WF) and Topographic (CT) Analysis (WF/CT Summary Display)

As previously explained, it analyses the aberrations of the internal optics.

THE iTRACE TOPOGRAPHIC SYSTEM

The iTrace uses a Placido format named Vista based on the hardware developed by Eyesys Vision Inc.

(Houston, Tx), one of the largest installed topographic systems in the world (fig. 18). The Placido design of the Vista is the same as that of the larger Eyesys 2000. Both systems cover the same area, the central cornea at around 0.6 mm to up to 10 mm in the normal peripheral cornea. In the new version, iTrace Combo (software 4.2), the Placido topographer is attached to the aberrometer in the same unit and a laser with a 655 nm wavelength is used to align the system.



Figure 18. Placido disks reflected in the cornea. With this screen (Verification Display) we can confirm that the measure has been correctly taken.

Although Placido topography has been thoroughly discussed in chapter 15 we are now going to describe the information provided by Eyesys Vista.

1. Standard **keratometric** readings in the zone of 3 mm.

2. Reading of the **refractive power of the cornea** in the central 3 mm zone. It is based in Snellen's law of refraction and an effective refractive power value of the central cornea is obtained. In theory, it would be valid to use that keratometric value in the calculation of IOL after corneal refractive surgery.

3. **Corneal index:** Inferior-superior index (I-S), Corneal uniformity index (CUI), corneal aspheric factor (Q), potential corneal acuity (PCA), spherical aberration of the cornea at 6 mm, ...

4. Topographic maps:

a) *Standard axial map:* Shows the curvature in a specific point of the corneal surface in the axial direction relative to the centre

b) *Local or tangential curvature map:* Measures the curvature in a specific point of the surface of the cornea

c) *Refractive map.* Based in Snellen's law. It gives us the refractive power in dioptric power. Emmetropia will show in green, myopia in warm colours and cool colours will indicate hypermetropia.

d) *Elevation map.* Shows the difference in elevation between a point in the corneal surface and a point in the surface of the reference sphere. Different reference morphologies can be chosen.

e) *Corneal wavefront map.* It shows both the total aberrations map and the different Zernike polynomials map. The coma map is very useful to plan intracorneal ring surgery.

The iTrace shows 5 different screens in CT Summary Display depending on the topographic maps that we want (fig. 19).

The corneal wavefront map gives us the information on the corneal aberrometry. The iTrace makes the calculations based on the data obtained through the Placido Eyesys Vista. By means of the refractive map a transformation in Zernike polynomials is made and the corneal aberrometry is obtained. By subtracting the corneal aberrations from the total aberrations, we obtain the aberrations of the internal optics, mainly caused by those produced by the crystalline.

Studying the aberrations can also help us to choose the model of posterior chamber lens for implantation in a patient whose crystalline is going to be removed. There are different models of intraocular lenses with different values of spherical aberrations (positive, zero

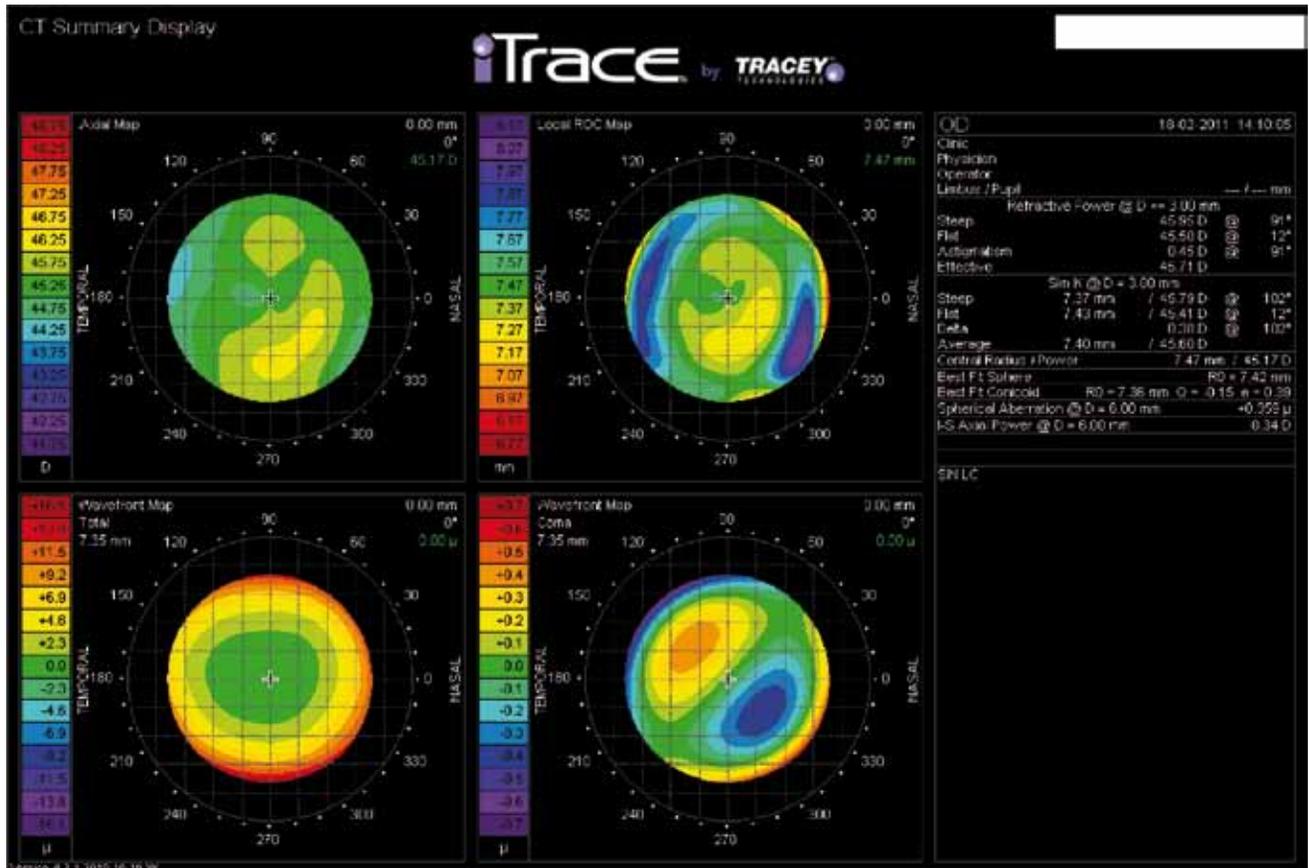


Figure 19. Topographic analysis (CT Summary Display) of a subclinical keratoconus. Observe coma (Wavefront Map, bottom right), which also matches the axis of the axial and local curvature maps

or negative). The model of the lens that is going to be implanted can be selected depending on the value of the corneal spherical aberration so that the total spherical aberration is the closest to zero. According to some studies, obtaining total spherical aberration close to zero would give us a better distance vision quality^{9,10}. Packer et al, carried out a study using the iTrace to this effect obtaining mean postoperative values Z (4,0) of 0.058 ± 0.056 ¹¹.

OBJECTIVE ACCOMMODATION MEASUREMENT

Accommodation is defined as the optical change induced by the eye's power when it focuses at different distances. There are subjective and objective methods to measure accommodation. Subjective methods do not differentiate passive depth of field due to miosis or ocular aberrations, nor do they measure the optical accommodative change in the power of the eye. These subjective methods overestimate the measurements^{12,13}. Therefore, any work to assess the accommodative aspects of the eye must

be done with an objective method. The most widely used objective methods are autorefractometers and aberrometers.

The iTrace has been used in several studies to measure accommodation^{12,14,15}. This possibility of measuring accommodation is based on patients being able to far away through the instrument. This allows the examiner to show stimuli at different distances to measure their accommodation power. Another, less used option, is to adjust the Badal optometer dioptrically to stimulate the accommodation. Due to the physical characteristics of the system up to 4.5 D of accommodation can be measured in an emmetropic eye. The accommodation measurement is based in a far stimulus (0 D of accommodative demand), measuring its refractive map and subsequently observing its difference with the refractive maps resulting from stimulus at different specific distances (figs. 20 and 21). In practice, it is done showing a near vision optotype in a calibrated stick in which we can see the specific distance at which the stimulus is presented. The differences between the refractive maps can be analysed both in quantitative values (obtaining the

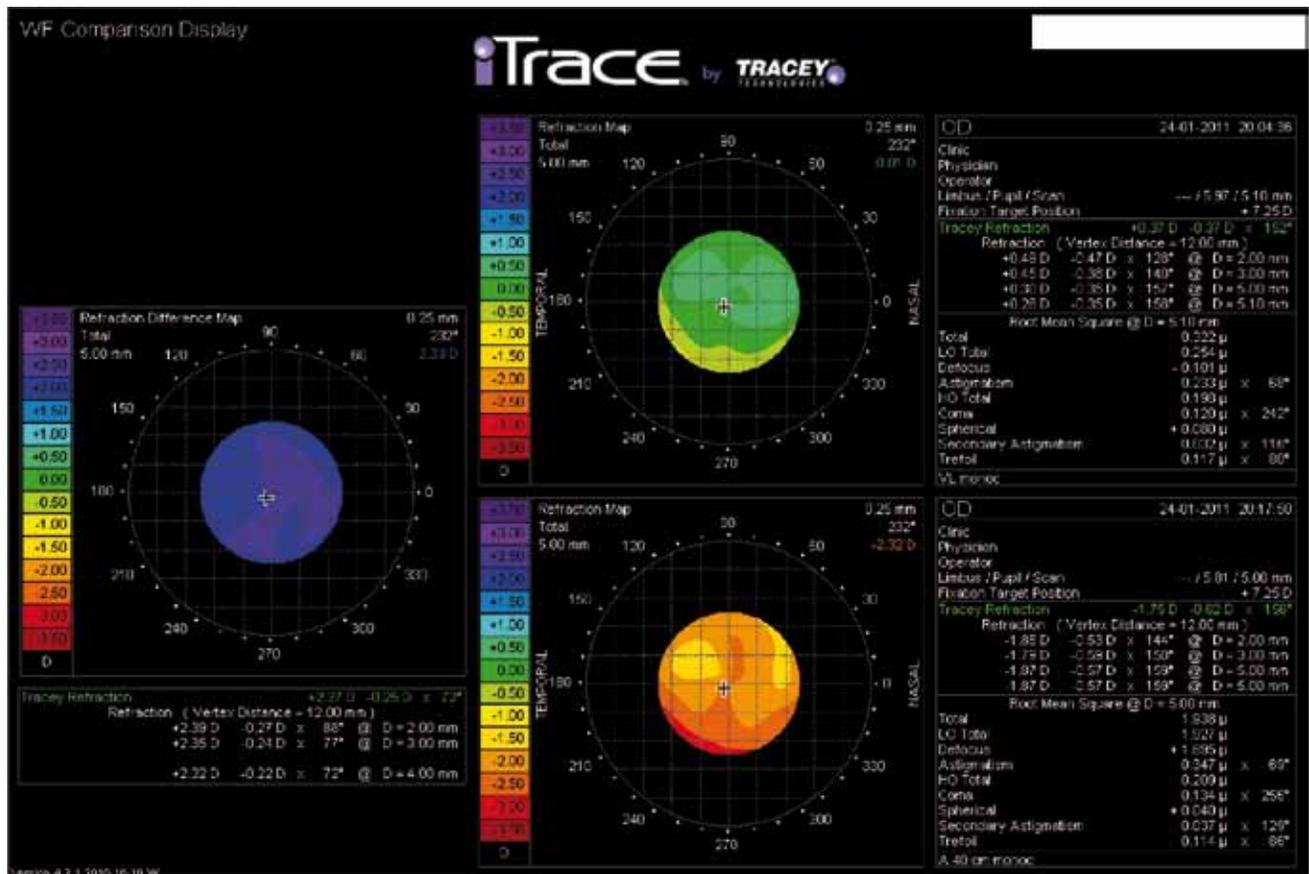


Figure 20. Analysis of the accommodative ability of a 30-year-old hypermetropic patient by means of the comparison of the refractive map observing a distance vision optotype (top map, almost all green) and afterwards, fixing a near vision optotype, 40 cm (bottom map with warm colours). The difference between both maps gives us the accommodation ability of the patient at this distance (left map, cool colours). The patient is accommodating at 2.37 D.

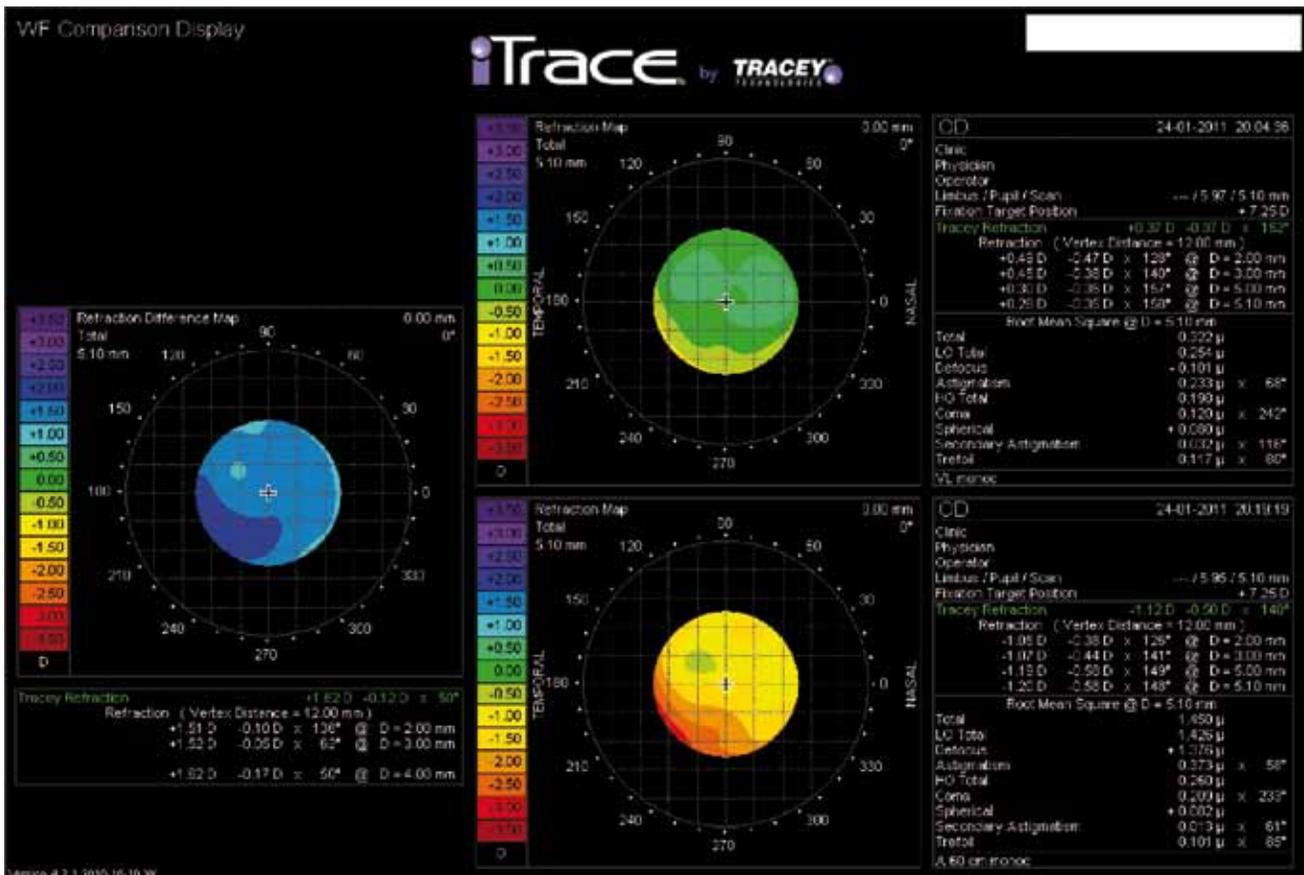


Figure 21. Analysis of the accommodative ability of the same patient, but in this case, with an accommodative stimulus at 60 cm. We see that the amount of accommodation used to focus the test is approximately 1.50 D as this test is farther away. Likewise, Total aberrations, LOA, HOA and multizone refraction of the iTrace can be analysed in each situation.

myopic change given by the accommodation power) and in qualitative values.

In the study of Win-Hall et al it was observed that in a presbyopic population (38-49 years) the average accommodative range measured by the subjective test (push-up) was 4.76 ± 1.32 D and with iTrace it was 2.9 ± 0.99 D (12). The overestimation of the accommodation measured by the subjective test had a range of 0.54-4.55 D.

The qualitative difference between the two refractive maps obtained at different distances usually results in a homogeneous spherical change adjusting to the classic model of accommodation. In other occasions, the patterns acquire an astigmatic or coma-like morphology. The cause of this might be that during the ciliary contraction the zonule does not relax homogeneously in its entire circumference, giving way to non-homogeneous patterns.

Changes in high order aberrations (HOA) can also be seen in the analysis of the accommodation. It is not easy to measure them as a miosis occurs during accommodation increasing the diffraction and depth of the focus. This miosis limits the iTrace measurement as it increases the density of the 256

rays examined, with a risk of overlapping. Numerous studies have demonstrated an increase in spherical aberration Z (4,0) as accommodation increases^{16,17}. According to some authors, this increase follows a linear correlation ($y = 0.031x + 0.049$; $r = 0.093$)¹² and is not of great magnitude as the miosis also increases the depth of the focus. In studies with iridectomised monkeys higher values were obtained for Z (4,0)¹⁷.

ADVANTAGES OF THE iTRACE AND COMPARISON TO OTHER ABERROMETRY SYSTEMS

There is a wide range of optical aberrations in the human eye. These aberrations must be measured in the most accurate and reproducible way. There is one main inconvenient, the retina can not be substituted by an optical detector, therefore, to measure visual aberrations light is projected forwards and backwards in relation to the eye in a double-pass phenomenon that creates another error as sight occurs in precisely one step.

The Tscherning aberrometer projects forward the image of a rectilinear grid into the eye; it is focused as a distorted image of the retina due to the lack of optical homogeneity of the eye. Aberrations are calculated from this distorted image. This technique is limited by the resolution of the aberroscope. Likewise, every point of the system is taken in one measurement; therefore, in a completely aberrated eye a cross-over of the points is possible.

Hartmann-Shack's technique uses a beam of light that goes into the eye and is reflected on the retina as a secondary source of light. This reflected light travels from the inside to the outside of the eye and is projected outside the pupil in a matrix of lenses. The number of lenses in the matrix limits the spatial resolution of this system, and the focal distance of the lenses limits its sensitivity. The problem of this system is its limited dynamic range. This system, as well as the Tscherning aberroscope, takes only one measurement simultaneously and it can result in a cross-over effect.

One of the advantages of Ray Tracing is the sequential capture of data. This means that there is no confusion in the analysis as each point is processed separately and sequentially. Second, the pattern of laser beams projected through the entrance pupil adapts to the pupil's size. The iTrace gauges the pupil size and projects all 256 points into a pupil as small as 2.5 mm or as large as 8 mm. The third advantage is that since each point is measured separately using linear detectors, the accuracy of measuring the centre of each point increases in comparison to other aberrometric systems. The main advantage of Ray Tracing over other aberrometric principles is that the x-y scanner can be programmed to analyse any other rectilinear or polar pattern.

There are many comparative studies between aberrometers^{5,8,18}. Some of them are detailed below:

In a study carried out by Liang & cols. 3 Hartmann-Shack aberrometers were compared (WaveScan, Zywave and Ladarwave); important discrepancies were found in high order aberration measurements¹⁹.

In a comparative study between the iTrace and automatic retinoscopy (Nidek OPD-Scan), important differences between the measurements of these two aberrometers are noted. The iTrace values for high order aberrations are higher. The iTrace also takes measurements quicker than the OPD-Scan and with less susceptibility to eye motion and tear film artefacts²⁰.

A comparative study of 6 aberrometers (iTrace, OPD-Scan, Zywave, WASCA, Multi-Spot Hartmann y Tscherning) concludes that generally speaking, all aberrometers produced comparable results, but those which examine less than 70 point data in a 6 mm pupil have a greater variance in their measurements (8).

In another study comparing the iTrace vs. Hartmann-Shack, it is concluded that the alignment of the aberrometer, the size of the pupil and how it compensates the accommodation are very important. Likewise, it is noted that the Hartmann-Shack can present saturation problems in corneas with high aberrations²¹.

Therefore, and broadly speaking, it has been noted that wavefront total RMS values are comparable between the different aberrometers, but when HOA RMS are analysed wide differences exist. Different results are found even when comparing aberrometers based on the same technology.

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