Clinical comparison of 6 aberrometers. Part 1: Technical specifications

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Purpose: To provide a detailed assessment of the techniques, technical features, and practical use of 6 aberrometers made available to our institution from September 2002 to January 2004.

Setting: Department of Ophthalmology, University Hospital Antwerp, Antwerp, Belgium.

Methods: A number of technical and practical parameters are listed for the Visual Function Analyzer (Tracey), the OPD-scan (ARK 10000; Nidek), the Zywave (Bausch & Lomb), the WASCA (Carl Zeiss Meditec), the MultiSpot Hartmann-Shack device, and the Allegretto Wave Analyzer including working principles, data acquisition, aberrometer alignment, wavefront calculation, and data analysis. Operator and patient comfort as well as practical advantages and disadvantages are discussed.

Conclusion: All devices met at least half the following parameters: alignment, correction for source wavelength, data averaging, measurement quality check, and inhibition of accommodation.

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Because aberrometry presents larger applications than enhancing the quality of the ablation zone in an excimer laser treatment, the choice of the most appropriate machine depends mainly on the ophthalmologist's practice style. Making a practical comparison among the devices available is not an easy task because of the variety of principles used; for example, ray tracing,[1,2] Hartmann-Shack,[3,4] Tscherning,[5] and automatic retinoscopy.[6] To our knowledge, only 2 reports[7,8] have attempted to make a comparative list of characteristics, but both relied on unedited information provided by the manufacturers, and the tables presented were incomplete. Additionally, each manufacturer used its own terminology, which might be confusing to nonspecialists.

The purpose of this study was to provide a number of technical and practical parameters that may be useful in choosing an aberrometer for daily clinical practice. The main focus is on wavefront measurements, rather than on their possible application in refractive surgery. The aberrometers under study are the following:

- Visual Function Analyzer (VFA; Tracey): based on ray tracing; can be used with the EyeSys Vista corneal topographer.
- OPD-scan (ARK 10000; Nidek): based on automatic retinoscopy; provides integrated corneal topography and wavefront measurement in 1 device.
- Zywave (Bausch & Lomb): a Hartmann-Shack system that can be combined with the Orbscan corneal topography system.

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- WASCA (Carl Zeiss Meditec): a high-resolution Hartmann-Shack system.
- MultiSpot 250-AD Hartmann-Shack sensor[9]: a custom-made Hartmann-Shack system, engineered by the Laboratory of Adaptive Optics at Moscow State University, that includes an adaptive mirror to compensate for accommodation.
- Allegretto Wave Analyzer (WaveLight): an objective Tscherning device

This study was conducted from October 2002 through January 2004. During this period, the companies of these aberrometers made their devices available to our institution.

We note that the results represent only the devices as they were made available to our department during the study period. Because the devices undergo constant alteration and improvement, we advise potential users to verify all parameters for each model and device.

Materials and Methods

The technical and practical parameters of the devices studied are shown in Table 1. The following sections discuss the importance of each parameter.

Principles Used to Measure Aberrations

These aberrometers comprise 4 techniques that are based on the principle of focal shift. This principle states that a perfect lens always refracts any incident light beam parallel to the lens' optical axis through its focal point (Figure 1, *top*). If the lens is aberrated, however, this is no longer true for each parallel incident beam. Instead, some of the beams are focused in front of or behind the focal point, so the cross-section point of the refracted beam with the focal plane appears to have shifted from the focal point. This is called *focal shift* and can be used as a definition of what is measured by an aberrometer.

When the incident beam is moved to another spot on the lens surface, the focal shift will vary in accordance with the lens' local aberrations in that spot. Mapping the relation between the various points of incidence and the corresponding focal shifts provides a general idea of the wavefront slopes in these positions. Using a statistical least-squares-fit procedure and (the mathematical derivatives of) Zernike polynomials, an estimate of the ocular wavefront can be found.

Starting from this common basic principle, aberrometers can be further categorized according to their respective technical properties. One possible classification can be based on subjective (psychophysical) and objective devices. The first category requires the patient to give some feedback during the measurement process; objective devices perform the entire measurement autonomously. In general, objective devices perform measurements faster than subjective devices. Subjective devices also rely completely on the patient's ability to communicate with the examiner, making these methods less useful for testing children or disabled patients.

Another subdivision can be based on the serial or parallel principle used in the different machines, referring, respectively, to a 1-by-1 measurement of the data points or an instantaneous collective measurement of all points. Parallel methods can be fast, whereas serial methods require longer measurement time. Serial methods, on the other hand, do not suffer from the crossover effect (discussed later) that may hamper parallel measurements.

A third classification can be based on the single or double-pass principle, indicating the number of times the measurement beam has to pass the aberrated eye optics. Because the light is aberrated at each passage, it is important to keep the number of passages as low as possible, preferably to 1. However, objective measurements cannot be performed in a single-pass way, creating the necessity to reduce the negative effects of double-pass using a number of optical tricks. Subjective methods, however, can easily be made single-pass.

A final classification can be based on forward projection of the measurements (ie, the focal shifts are projected on the retina) or backward projection (ie, the focal shifts are projected directly on the camera). A backward projection requires a source on the retina, such as a reflection of a narrow laser beam. Because this narrow laser beam remains relatively unaffected by the first pass, it can be considered a good approximation of single–pass.

In this work, we have chosen to use the serial–parallel classification: 2 serial and 2 parallel methods are discussed further. Only the most important aberrometer components are discussed to illustrate the working principles. Components such as the computer used for data processing or prefocus lenses for refraction compensation are not included, although they are required for proper functioning of the devices.

Ray-Tracing Principle. This is a serial, double-pass method using forward projection, which can be implemented in both an objective[1,2] and a subjective way (Figure 1, *center left*).[10] This technique is the best approximation of the basic focal shift principle described earlier.

Ray tracing uses a narrow laser beam that is directed into the eye parallel to the eye's line of sight by means of an *x–y* scanner. Once in the eye, the local aberrations in the beam's entry position cause a focal shift of the retinal image with respect to a certain reference position. Using a beam splitter and lens L_2, the retinal image is captured on a linear array of photodetectors and is available for further processing. The *x–y* scanner, comprising 2 separate scanners for the *x*- and

Table 1. Technical comparison of the aberrometers studied.

Measurement/ Calculation Details and Data Analysis	VFA	OPD-scan	Zywave	WASCA	MultiSpot	Allegretto
Device details						
Device type or serial number	2066-1	ARK 10000	Zywave II (2.0.1)	Not available	I-a	1071
Software version	1.00	1.11a	4.45 SP1	1.41.6	1.5	4.10
Method	Ray tracing	Automatic retinoscope	Hartmann-Shack	Hartmann-Shack	Hartmann-Shack	Objective Tscherning
Measurement details						
Wavelength (nm)*	650	808	785	850	780	660
Chromatic correction†	No	Yes	Yes	Yes (555 nm)	No	Yes (546 nm)
Maximum number of samples*	256	1440	80	1452	180	168
Sample grid geometry*‡	Polar	By meridian	Rectilinear	Rectilinear	Rectilinear	Rectilinear
User defined grid size*‡	Yes	No	No	No	No	No
Measurement speed*	<50 ms	<0.4 s	<1 s	13 ms	<30 ms	40 ms
Maximum measurable pupil size (mm)†‡	8.0	6.0	8.5	9.0	8.0	8.0
Dioptric range prefocus (D)*‡	Sph: −15 → +15	Sph: −20 → 22 Cyl: 0 → ±12	Sph: −14 → 8 Cyl: 0 → ±5	Sph: −15 → 7 Cyl: 0 → ±5	Sph: −15 → 10 Cyl: 0 → ±6	Sph: −12 → 6 Cyl: 0 → ±4
Automatic check of measurement quality*‡	Number of rejected spots	Yes	Repeatability criteria	No	Comparison tilts with spots	Comparison tilts with spots
Automatic averaging of measurements*†	No	3 measurements	Best 3 of 5	No	User defined	User defined
Inhibition of accommodation†	Fogging	Fogging	Fogging	Object at infinity	Object at infinity/ adaptive mirror	Fogging (user defined)
Possibility of automatic measurement*‡	Yes	No	No	No	No	Yes
Speckle reduction†	Low-pass filter	Does not apply	Averaging	Pinhole	"Wobbling mirror"	Averaging/ low-pass filter
Alignment						
Measurement axis†	LoS	Visual axis	LoS	LoS	LoS	LoS
Patient target*‡	Red cross	Balloon on horizon	Mountain and road	Spider web	Small circle	Star in yellow circle
Alignment procedure for operator*‡	Variable line pointing to pupil center	Dots parallel to pupil	Circle parallel to pupil	Pupil inside crosshair/offset values	2 circles and half cross/calculated pupil	Purkinje reflexes and pupil center
Calculation details						
Number of Zernike polynomials used*‡	27 (6th order)	27 (6th order)	20 (5th order)	Up to 65 (10th order)	Up to 27 (6th order)	Up to 27 (6th order)
Pupil size for Zernike polynomials*‡	Automatic/user defined	6 mm	Pupil size	Automatic/user defined	Automatic/user defined	Automatic/user defined

Table 1 (cont.)

Measurement/ Calculation Details and Data Analysis	VFA	OPD-scan	Zywave	WASCA	MultiSpot	Allegretto
Report axis*†	LoS	LoS	LoS	LoS	LoS	LoS
Consistent with OSA Zernike notation?‡	Yes	No (not normalized)	Not yet (Born & Wolf notation)	No (inverted sign)	Yes	Yes (+own notation)
Possibility of aberration film sequence*‡	No	No	No	2 frame/s	Video rate	No
Data analysis						
Raw data*‡	Yes	No	Yes (mesh)	Yes	Yes	Yes
Refraction*‡	Yes	Yes	Yes	Yes	Yes	Yes
Wavefront*‡	Yes	Yes	Yes	Yes	Yes	Yes
Higher-order wavefront*‡	Yes	Yes	Yes	Yes	Yes	Yes
RMS*‡	Yes	Yes	Yes	Yes	Yes	Yes
3D wavefront*‡	No	No	Yes	Yes	Yes	Yes
Total refraction map*‡	Yes	Yes	No	No	Yes	Yes
PSF*‡	Yes	No	Yes	Yes (real data)	Yes	Yes
MTF*‡	No	No	No	No	No	No
Visual acuity*‡	Yes	No	No	Yes	Yes	No
Error estimate map*‡	Yes	No	No	No	Yes	Yes
Irradiance map*‡	No	No	No	Yes	No	No
Zernike coefficient values (on screen)*‡	Yes	Yes	Yes	Yes	Yes	Yes
Change of refraction with pupil size*‡	Yes (3, 4.5, 6 mm zones)	Yes (3, 5, 7 mm zones)	Yes (3 mm pupil size)	Yes (user defined)	No	Yes (user defined)
Miscellaneous						
Data export of Zernike coefficients*‡	Yes	Yes	Yes	Yes	Yes	Yes
Data export of wavefront maps*‡	Yes	Yes	No	No	Yes	Yes
Customized printout*‡	Yes	Yes	Yes	Yes	Yes	Yes
Calibration check*‡	Test eye	Test eye	2 test eyes	Test eye	Test eye	Test eye
Requirement for dilation*†	Small pupils	Small pupils	Small pupils	Small pupils	Small pupils	Small pupils

These data undergo constant adjustments and represent only the devices made available by the companies to our institution from September 2002 to January 2004. Some of the data in this table have been published.[7,8]

Cyl = cylinder; LoS = line of sight; MTF = modulation transfer function; OSA = Optical Society of America; PSF = point spread function; RMS = root mean square

*Source: Aberrometer manual

†Source: Company associate

‡Observation by the authors

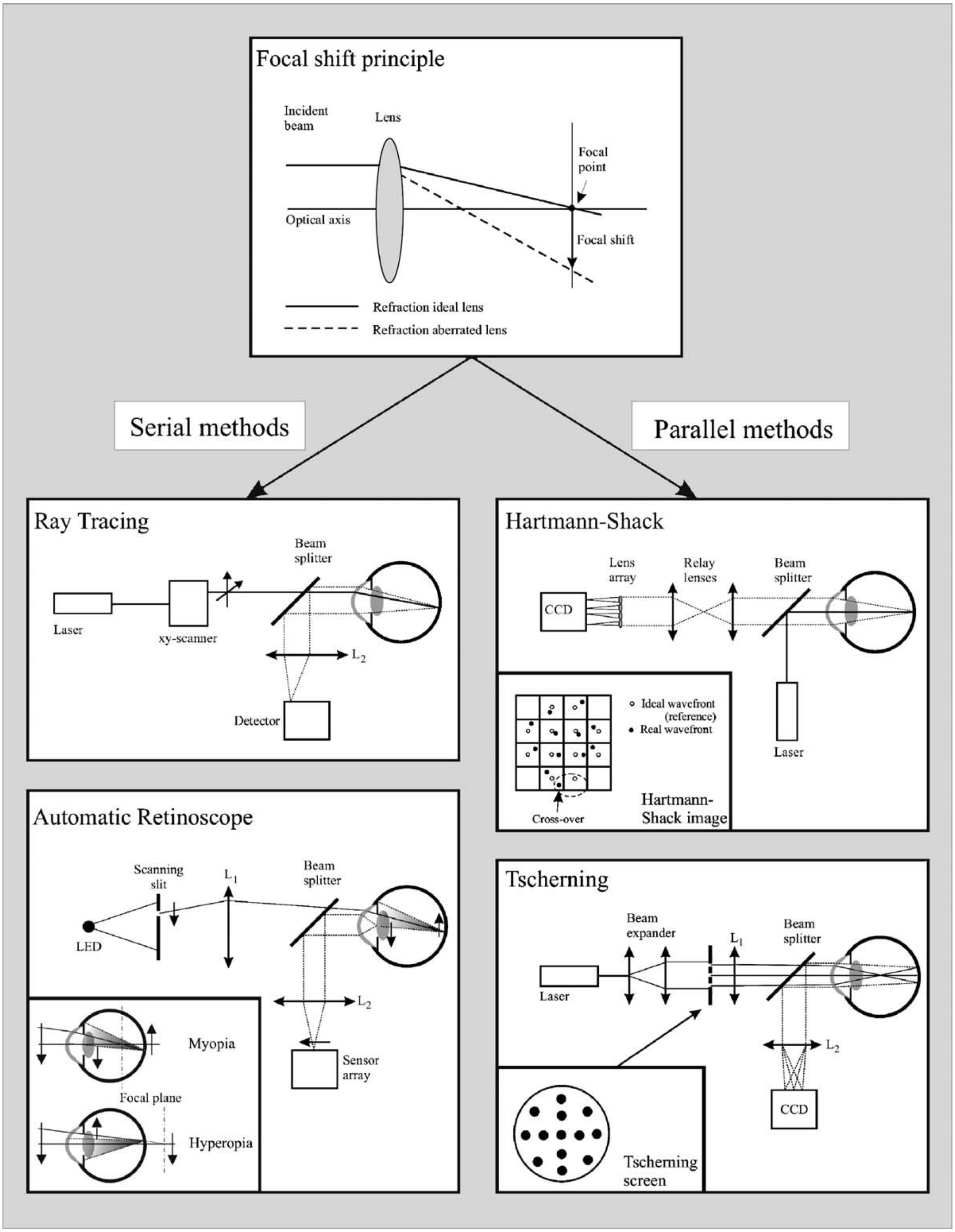

Figure 1. The principles of the wavefront sensors: *Top*: Skew ray. *Center Left*: Ray tracing. *Center Right*: Hartmann-Shack. *Bottom Left*: Automatic retinoscope. *Bottom Right*: Tscherning. Single-head arrows indicate direction of movement for beams.

y-directions, moves the beam repeatedly to a new entry position until homogeneously spread measurements are available for the whole pupil area.

Ray tracing is a simple, highly flexible technique. In principle, the *x*–*y* scanner could be programmed to include scan geometries other than the standard rectilinear or polar scan grids. Its uncomplicated nature also makes it robust for extreme aberrations.

Principle of the Automatic Retinoscope.[6] This is an automated version of the handheld retinoscope, implemented in an objective, serial, and double-pass way (Figure 1, *bottom left*). It uses focal shift in a different way (figure inset), starting from the observation that the retinal image of a light beam coming from a superior direction is located below the optical axis in a myopic eye and above the optical axis in a hyperopic eye. Because the retina can be considered a spherically concave mirror (reflecting about 4% of the incident light), the beam is reflected back in more or less the original direction in a myopic eye. In a hyperopic eye, however, the reflection is directed to the opposite side of the pupil. Moving the incident beam along a certain pupillary meridian (indicated by arrows in the figure) will result in a reflected beam that goes in the same or the opposite direction as the incident beam. The difference in direction and the ratio between the speed of the incident beam and that of its reflection can then be used to estimate the ocular refraction along this meridian.

The automatic retinoscope uses a light emitting diode (LED) source that is placed behind a screen with a fast-moving slit. Using lens L_1, the image of the slit is projected on the pupil plane, where a portion of the light will pass the pupil opening. Depending on the ocular refraction along the scanned meridian, the reflected beam moves with a specific speed and direction. This is registered by projecting the pupil plane on an array of photosensitive diodes using a beam splitter and lens L_2. When the orientation of both the scanning slit and the diode array are changed to measure another meridian, an ametropia map (in diopters) is obtained that can be transposed into a wavefront map (in microns).

Hartmann-Shack Principle.[3,4] This is an objective, parallel, double-pass method using backward projection (Figure 1, *center right*). A Hartmann-Shack device uses a narrow laser beam that is sent along the ocular line of sight into the eye, where it reflects on the retina. This reflection serves as secondary source that illuminates the pupil area from behind. The outgoing light is then guided through a set of relay lenses that projects the pupil plane onto an array of tiny lenses that splits up the wavefront into a number of individually focused spots on a charged coupled device camera. Because of focal shift, the resulting spot pattern (figure inset) shows spot displacements compared with the reference positions. This way, the wavefront slopes are determined for the entire pupil at once.

However fast and uncomplicated (because no moving parts are required), the performance of this parallel method is limited to aberrations that are not too complicated. To determine the focal shift directly, each reference position is allocated a neighborhood in which the shifted spots are directly associated with a specific reference position (square grid in figure inset). For rapidly varying wavefronts with steep slopes, this can result in focal shifts becoming so large that spots cross over to neighborhoods belonging to another reference position (bottom of inset). This makes it impossible to determine the focal shift in these areas. Crossover can be partially prevented by using prefocus lenses that correct the ocular refraction.

Tscherning Principle. This is a parallel, double-pass method using forward projection that can be implemented in both an objective[5] and a subjective way (Figure 1, *bottom right*).[11] Contrary to the Hartmann-Shack method, the Tscherning aberrometer uses not 1 but a group of laser beams that enter the eye. These beams are generated using a wide laser beam passing through a screen with a large number of round holes. Lens L_1 projects an image of the Tscherning screen onto the retina, resulting in a spot pattern resembling a Hartmann-Shack pattern, where again spots are displaced due to focal shift. The retinal image is then retrieved using a beam splitter and lens L_2. The distortions in the retinal spot pattern are then used to obtain the wavefront as before.

The Tscherning method may also suffer from the crossover effect, as is the case with the Hartmann-Shack method. Similar countermeasures are implemented to prevent crossover.

Measurement Details

- Wavelength: This is the color of the light used for measurements.
- Compensation of chromatic aberrations: This is the calculated compensation of the chromatic defocus using a numeric model.
- Maximum number of samples: In general, the more samples taken within the pupil area, the more accurate the measurement will be. However, because the data processing following the measurement plays an equally important role, a large number of samples does not necessarily mean a more reliable measurement.
- Sample grid geometry: This describes the geometry of the sample grid in the pupil plane.
- User-defined grid size: This offers the user the possibility of modifying the grid size.
- Measurement speed: This refers to the time required for 1 measurement.
- Maximum measurable pupil size: This refers to the largest pupil size that can be measured.
- Dioptric range of prefocus: This is the range within which the patients' refractive error can be compensated by the internal lenses of the aberrometer.
- Check for quality of measurement: This estimates the reliability of a measurement, either automatically by the computer or afterward by the user.
- Automatic averaging of measurements: This function preprocesses the data by averaging.
- Possibility of automatic measurement: This indicates whether the aberrometer can perform a measurement

automatically after optimal alignment has been achieved.

- Inhibition of accommodation: Wavefronts change drastically with accommodation of the crystalline lens. It is therefore necessary to eliminate accommodation using optical tricks. One commonly used method is to put the target at optical infinity. Another method, called *fogging*, is to make the target out of focus so that accommodation will not help one attain a sharp image. A third approach is the use of adaptive optics.
- Speckle reduction: Coherent laser light often forms granular dots in the images because of small local interferences which complicates the determination of the spot centers. This can be avoided by breaking the light's coherence, by averaging, or by using special filters (either in the hardware or software of the device).

Alignment

- Measurement axis: This is the axis along which a measurement is taken. This can be done along the line of sight (LoS), which is the line connecting the fovea, the pupil center, and the fixation target, or along the visual axis (connecting the fovea, the eye's nodal points, and the fixation target). Even though these axes differ only slightly from each other, the difference in wavefront can be considerable. The Optical Society of America (OSA) standard[12] advises use of the LoS because it is physiologically the most important axis. Conversions between both axes are possible, but not advisable as it would introduce a number of errors into the calculations.
- Patient target: This refers to the depiction of the fixation target to minimize patients' eye movement.
- Alignment procedure for operator: To ensure that the aberrometer optics are well aligned with the LoS, it is imperative that a good alignment procedure is in place. This can be done by using the landmarks of the patient's physiology or by creating reflections that can serve as artificial landmarks.

Calculation Details

The time needed to complete the data processing is an important parameter. Because this parameter varies strongly with the type of computer used, however, it was not included in this study.

Most of the following calculation parameters have little clinical interest and are only useful when reporting numerical Zernike data.

- Number of Zernike polynomials used: This parameter indicates the spatial resolution of the wavefront image. The more Zernike polynomials used, the higher the spatial resolution.
- Pupil size for Zernike polynomials: Zernike polynomials are mathematical functions defined on a unit circle. When expressing wavefront aberrations in terms of Zernike coefficients, it is imperative that this is accompanied by the pupil diameter over which the aberrations were determined. These coefficients will change when the measurement is repeated for another pupil size and may cause problems if data from different pupil sizes are compared. Calculations have been described[13] that allow one to derive the Zernike coefficients of a smaller pupil size from a larger one.
- Report axis: This is the axis used to report the Zernike polynomials. According to the OSA standards for reference axes,[12] this should be the LoS.
- Consistent with OSA Zernike notation: This is the sign and normalization convention used to report the Zernike coefficients that were determined by the OSA standards,[14] although a number of other conventions are currently still in use.
- Possibility of making aberration film sequence: Some devices offer the possibility of performing a series of measurements, allowing an animated reconstruction of the data.

Data Analysis

The following are all the data displays available:

- Raw data: an image of the original spot diagram
- Refraction: sphere, cylinder, and axis
- Wavefront: total wavefront aberrations
- Higher-order wavefront: remaining wavefront aberrations after correction of the sphere and cylinder.
- Root mean square (RMS), a parameter defined by $RMS = \sqrt{\Sigma_i Z_i^2}$ (sum is taken over all Zernike coefficients Z_i), providing a measure for wavefront flatness. Because this formula can be easily modified by including only selected Zernike coefficients, many types of RMS can be defined such as total RMS (all coefficients, except the tilts), higher-order RMS (all coefficients from radial orders higher than 2) and nth order RMS (all coefficients belonging to the nth radial order).
- 3D wavefront: 3-dimensional display of the wavefront. This can be a useful tool for estimating the shape of the measured wavefront.
- Total refraction map: refraction map of the whole eye optics calculated from the wavefront
- Point spread function (PSF): image of a point source as seen by the patient calculated from the wavefront.
- Modulation transfer function (MTF): indication of the contrast with which lines of specific spatial frequencies can be perceived by the patient.
- Visual acuity: simulation of the Snellen "E" as seen by the patient calculated from the measured wavefront.
- Error estimate map: regional map of the difference between the measured data and the data simulated using the Zernike polynomial fit; this may be useful for quality control.

- Irradiance map: image of the pupil area in which the amount of light passing through each section of the pupil is indicated; this can be used for mapping opacities in the eye optics.
- Zernike coefficient values (on screen): numeric values of the Zernike polynomial coefficients shown on screen.
- Change of refraction with pupil size: graph or table in which the refraction is set in function of the pupil size.

Miscellaneous

The following properties could not be included in the previous categories:

- Data export of Zernike coefficients: the option to export the numeric values of the Zernike coefficients in a file
- Data export of wavefront maps: the option to export the wavefront image (or another illustration) in a file
- Customized printout: the option to modify the printout according to the examiner's needs
- Calibration check: method for calibration
- Requirement for dilation: to determine whether dilation of the pupil in recommended before measuring

Results

The values of the parameters for each aberrometer are shown in Table 1. Note that these data undergo constant adjustments and represent only the devices made available by the companies or their Belgian associates to our institution from September 2002 to January 2004.

Principles Used to Measure the Aberrations

The VFA uses ray tracing, and the OPD-scan uses automatic retinoscopy. Three devices use the Hartmann-Shack principle (Zywave, WASCA, and MultiSpot), and the Allegretto uses the Tscherning principle.

Measurement Details

- Wavelength: Each device uses a monochromatic LED or laser source that emits red or infrared light (ranging from 650 nm for the VFA to 850 nm for the WASCA). At these wavelengths, the measured aberrations will be slightly different from the most relevant aberrations in the middle of the visual spectrum. In particular, the sphere can differ by as much as 0.7 diopters (D) between infrared and green wavelengths.
- Compensation chromatic aberrations: Only the MultiSpot and the VFA lack this feature. However, both devices will include this feature in the next software release.
- Maximum number of samples: This parameter ranges from 80 (Zywave) to 1452 (WASCA).
- Sample grid geometry: All the devices use a rectilinear sample grid. The VFA, however, scans over a polar (concentric) grid and the OPD-scan measures over a series of meridians.
- User defined grid size: Only the VFA has this feature, which can generate grid sizes from 2 to 8 mm.
- Measurement speed: The WASCA performs its measurements in 0.013 second. The other devices need 0.03 to 0.50 second.
- Maximum measurable pupil size: This parameter ranged from 6 mm (OPD-scan) to 9 mm (WASCA).
- Dioptric range of prefocus: The dioptric ranges of the devices are comparable (mean -15 D $\rightarrow$ 7 D; cylinder 0 $\rightarrow$ ± 5 D), with an exception for the OPD-scan that has a range of -20 D $\rightarrow$ $+22$ D (cylinder 0 $\rightarrow$ ± 12 D).
- Automatic check for quality of measurement: Of the 6 devices, 5 provide this estimation. The VFA estimates the reliability of the data points by rejecting points having an intensity below a certain threshold. Measurements with up to 3 rejected points are still acceptable. Alternatively, the user can reject data points. In the OPD-scan, this is done automatically. Faulty measurements can immediately be redone. The Zywave calculates the "repeatability criteria," which should stay below a certain threshold determined by the manufacturer. The MultiSpot device provides an error map in which the calculated wavefront is used to recalculate the corresponding spot pattern. This calculated spot pattern is then compared with the experimentally determined one, and the deviations are shown on the map. The Allegretto uses a similar principle. The WASCA has no quality check.
- Automatic averaging of measurements: With 4 of the 6 machines, some preprocessing of the data occurs by averaging. The OPD-scan averages 3 separate measurements and checks for their quality. Any wrong measurement is rejected and repeated. The Zywave does 5 measurements and uses the repeatability criteria to determine the best 3 for

averaging. The MultiSpot device records the wavefronts during a number of seconds. The operator can later select a period over which the averaged wavefront is calculated. The Allegretto takes 4 measurements that can be manually selected to be used for averaging. Neither the WASCA nor the VFA uses averaging.

- Inhibition of accommodation: The VFA, OPD-scan, Zywave, and Allegretto use fogging, whereas the WASCA and the MultiSpot place the object at optical infinity. With the Allegretto, the fogging can be turned off if necessary. The MultiSpot also has the option of compensating the accommodation in real time using an adaptive mirror that is controlled using a feedback loop that minimizes the total aberrations.
- Possibility of automatic measurement: Only the Allegretto and the VFA have this option. In both cases, an autonomous measurement is taken as soon as the best possible alignment is achieved.
- Speckle reduction: This is achieved using numerical filters (VFA, Allegretto) or by averaging multiple measurements (Zywave, Allegretto). The MultiSpot and the WASCA use a "wobbling mirror" and a pinhole, respectively. Because the OPD-scan uses a low-coherence LED source, speckle reduction is not required.

Alignment

- Measurement axis: All devices measure along the LoS. Only the OPD-scan uses the visual axis and converts the results to the LoS standard.
- Patient target (Figure 2): Most targets point toward the center, enhancing patient fixation. Only the Zywave has an off-center target (Figure 2, *C*), making the patient more inclined to look away. This may result in off-axis readings.
- Alignment procedure for operator (Figure 3): In 3 of 6 devices, this procedure consists of the alignment of a fixed circle (Figure 3, *A*: OPD-scan and Zywave; no image available for the OPD-scan) or of cross overlay (Figure 3, *B*: WASCA) and the pupil itself. This method depends solely on the operator's skill and is therefore sensitive to errors both along the optical axis and in the horizontal and vertical direction. The WASCA offers offset values that, in the "free-running mode" can also be used as an alignment tool. The VFA determines the pupil edge, from which the pupil center can be found (Figure 3, *C*). The misalignment of the device's optical axis with respect to the pupil center is indicated by a green line. Using this line, the alignment can be corrected. The MultiSpot device (Figure 3, *D*) uses 2 circles, each with a half cross, for positioning along the visual axis. The horizontal positioning is done visually by

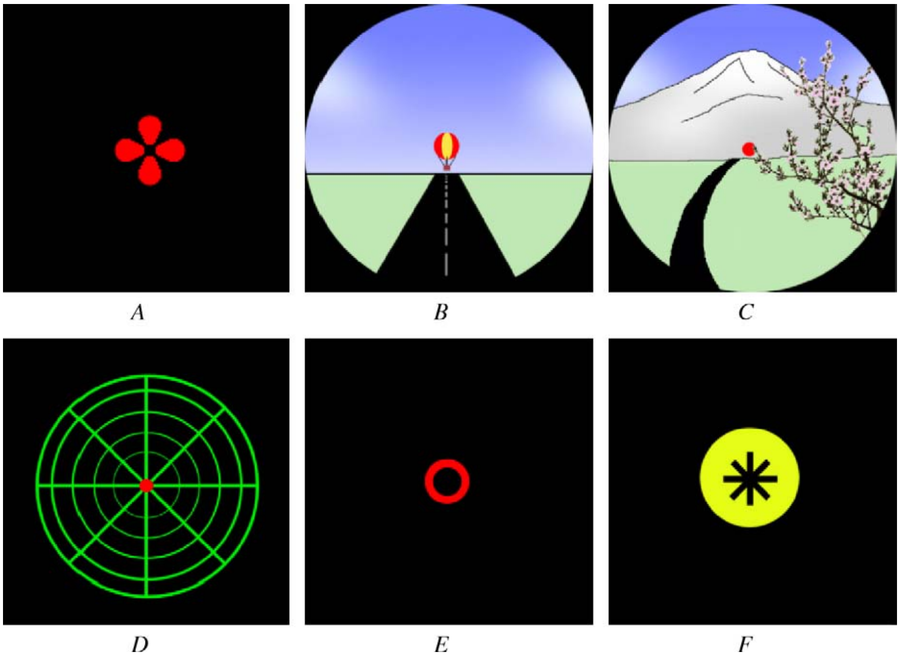

Figure 2. Reproductions of the fixation targets for the patient: *A*: VFA. *B*: OPD-scan. *C*: Zywave. *D*: WASCA. *E*: MultiSpot. *F*: Allegretto.

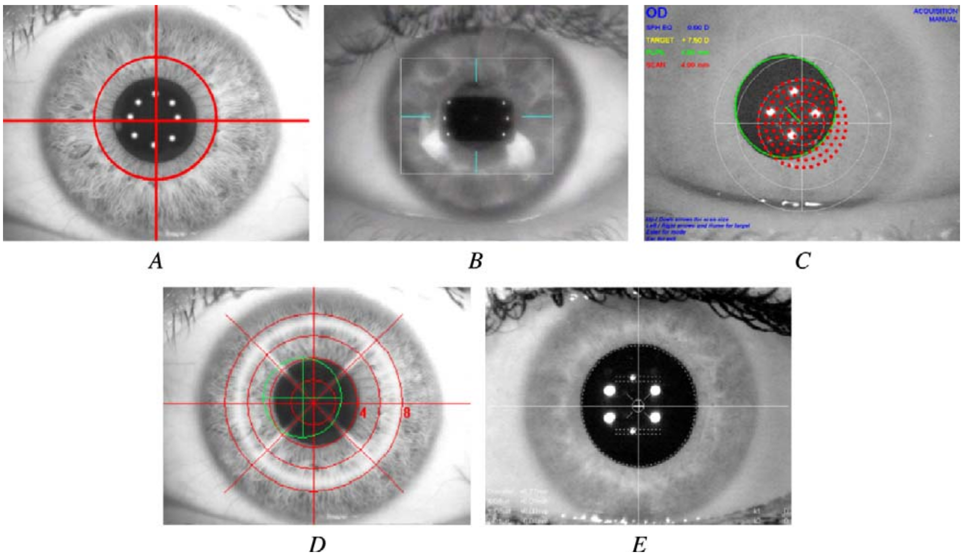

Figure 3. Reproductions of the live pupil images used for alignment of the aberrometer in increasing degree of complexity. *A*: Zywave. *B*: WASCA. *C*: VFA. *D*: MultiSpot. *E*: Allegretto. An image of the OPD-scan alignment screen could not be obtained.

aligning a series of concentric circles with the physiologic pupil as well as by aligning a calculated pupil. The calculated pupil is optically conjugated in size and location with the spot image on the CCD camera. The Allegretto uses an elaborated alignment procedure (Figure 3, *E*). First, the edge of the pupil is determined automatically to find its center, which is marked by a small cross. Next the device is moved along the optical axis until 2 reflections on the cornea ("Purkinje reflections") coincide with an overlay line. Finally, the cross in the pupil center has to coincide with an overlay cross for a horizontal and vertical alignment. Because this procedure is demanding for the operator and because of the low alignment tolerance (100 μm), an automatic measurement procedure has been included.

Calculation Details

- Number of Zernike polynomials used: This parameter varies from 20 (5th order) for the Zywave up to 65 (10th order) for the WASCA. The MultiSpot, the Allegretto, and the WASCA are able to determine how many polynomials should be used by estimating the data quality and pupil size. However, this selection can also be made by the user. The OPD-scan, Zywave, and VFA use a fixed number of Zernike polynomials.

In the latest software edition of the WASCA, the "zonal reconstruction" technique has been introduced for wavefront reconstruction. This no longer relies on Zernike polynomials or the pupil shape. If desired, the Zernike coefficients can be calculated.

- Pupil size for Zernike polynomials: The devices studied use a fixed pupil size of 6 mm (OPD-scan), the physiological size (Zywave), or a user-defined size (WASCA, MultiSpot, Allegretto, and VFA).
- Consistent with OSA Zernike notation: Only the MultiSpot and the VFA comply with this standard. The OPD-scan and the WASCA make an approximation but without normalization or inverted signs. The Zywave and Allegretto use different notations but will include the OSA Zernike standard in their new software.
- Possibility of aberration film sequence: The WASCA offers the option of making short 10-frame movies of a wavefront change. The MultiSpot can record wavefronts up to 20 seconds (600 frames) and store them as a list of Zernike coefficients.

Data Analysis

- Raw data: Most aberrometers provide raw data in various ways. Because of the different working principles of the OPD-scan, raw data are not available for it.
- Refraction: All the aberrometers provide this feature.
- Wavefront: All the aberrometers provide this feature.
- Higher-order wavefront: All the aberrometers provide this feature.

- RMS: All the aberrometers provide various types of RMS, including total RMS, higher-order RMS, and the RMS for a number of radial or angular orders.
- 3D wavefront: Four of the aberrometers provide this feature, and the OPD-scan and VFA will include it in their next software release.
- Total refraction map: This feature is available in the OPD-scan, the MultiSpot, the Allegretto, and the VFA.
- PSF: All aberrometers, except the OPD-scan, which will include it in the next software release, provide this feature. The WASCA provides the retinal spot image, which is an image of the PSF on the retina; the other aberrometers calculated the PSF from the wavefront.
- MTF: None of the aberrometers provide this feature.
- Visual acuity: This feature is available in the WASCA, MultiSpot, and VFA devices.
- Error estimate map: This feature is available in the MultiSpot and the Allegretto. The former shows a color map, and the latter superimposes the calculated spot over the original spot pattern.
- Irradiance map: This feature is only available with the WASCA.
- Zernike coefficient values (on screen): All the aberrometers provide this feature.
- Change of refraction with pupil size: Available in the Zywave as a graph. The other devices show either the refraction for a fixed set of pupil sizes (OPD-scan, VFA) or allow the user to change the pupil size (WASCA, Allegretto). The MultiSpot does not have this feature.

Miscellaneous

- Data export of Zernike coefficients: All aberrometers provide this feature. The OPD-scan, Zywave, and MultiSpot provide the coefficients for the entire measured pupil, and the VFA gives the coefficients for 4 pupil sizes. With the WASCA and Allegretto, the user can determine the size.
- Data export of wavefront maps: Only the Zywave and the WASCA lack this feature, both of which export only Zernike coefficients.
- Customized printout: All the aberrometers provide this feature.
- Calibration check: All the aberrometers use 1 or 2 test eyes as a calibration check.
- Requirement for dilation: In all cases, the manufacturers recommend dilation of the pupil to enlarge the measurement area.

User and Patient Parameters

These subjective parameters are not included in Table 1. They represent our experience and patients' impressions about the devices as they were available to us in the period from September 2002 to January 2004.

Patient Comfort. How does the patient experience the measurement?

- VFA: No problems.
- OPD-scan: No problems.
- Zywave: No problems.
- WASCA: The spider web target was tiring to some patients after a short time.
- MultiSpot: No problems.
- Allegretto: The measurement flash was sometimes experienced as uncomfortable. The constantly changing sound of the step motors is distracting for some.

Operator Comfort. How does the operator experience the measurement (very easy, easy, short learning curve, long learning curve)?

- VFA: Requires a short learning curve to operate.
- OPD-scan: Easy to use with comprehensive software.
- Zywave: Very easy to use.
- WASCA: Easy to use.
- MultiSpot: Requires a long learning curve to operate.
- Allegretto: Requires a short learning curve to operate; comprehensive software. The recalibration of the step motors every 5 measurements is time consuming.

Discussion

VFA

This is the only device that uses ray tracing, making it very flexible and robust for extreme aberrations. Measurements were obtained in pathologic conditions, such as cataract or corneal disease. The VFA also allows a large amount of freedom to the operator during and after the measurements.

If the optical target is removed, the patient is able to see through the device to a distant target. This way, the patient's accommodation can be tested directly by varying the distance between the target and the eye.

The VFA can be integrated with EyeSys Vista corneal topographer, so the anterior corneal aberrations can be subtracted from the total aberrations.

OPD-scan

This device uses automatic retinoscopy and also has an integrated corneal topographer. The OPS-scan provides a large list of corneal and refractive maps that can be interesting for a closer study of the eye's refraction. The compact design with the integrated computer and corneal topographer is ideal for small practices.

When using this device, it is important to make sure the pupil is fully dilated (no size variations during the measurement) to avoid irregular shapes of the calculated pupil. To export Zernike polynomial data from the OPD-scan, it is necessary to ensure that the minimal pupil diameter is 6 mm because the polynomials are calculated by default for this diameter. This means that for smaller pupil sizes, measurements are shown for areas outside the physiologic pupil, introducing erroneous Zernike coefficients.

During measurement, there is an automatic quality check. However, sometimes this automatic check fails to reject a bad measurement. Because the user cannot reject bad measurements, the whole procedure must be redone.

The alignment procedure is not elaborated and needs a steady hand of the operator. Using such a system, it is easy to introduce slight misalignments in the wavefront measurement, resulting in erroneous values of the tilt and the coma aberrations.

In the next software release, the corneal topography and the wavefront map can be linked to each other, which offers the option of subtracting the corneal aberrations from the total aberrations. This can be interesting for studying the wavefront effects of cataract or IOLs, for example.

Zywave

With this device, every step of the measurement process is done by consecutively clicking the button on the joystick. In 1 measurement, 5 spot patterns are recorded, and the best 3 are automatically selected using the repeatability criteria.

During our evaluation period, there was a healthy patient for whom 4 of 5 samples showed a cylinder of 0.5 D and 1 showed a clearly false value of −4.0 D. The system failed to recognize this extreme value and gave the final astigmatism value of −3.75 D, a correction that did not correspond to the patients' objective refraction. Repeated measurements on this patient showed similar results.

This devices offers the option of plotting the refraction as a function of the pupil diameter. It should be kept in mind that not all calculated points are equally accurate because of higher-order aberrations. Adding error bars to this graph would benefit the clinical value.

The alignment system relies on the alignment of a circle and a crosshair with the pupil edge. This simple alignment may introduce errors into the measurements, as well as the fixation target, which may be confusing to the patient. One alternative is to ask the patient to look slightly above the red dot of the laser source for fixation.

Combined use of the Zywave with the Orbscan II corneal topographer would be useful. This option is not yet available, however.

WASCA

This Hartmann-Shack-based device measures the highest number of samples. It also shows the presence of missing data points, which are represented by blanks on the wavefront map. To avoid errors, however, no holes can be allowed inside the Zernike pupil when the polynomials are calculated.

The free-running mode is interesting because it shows a moving image of the wavefront, allowing study of accommodative changes and the option of saving short wavefront movies.

The alignment procedure is limited, although this can be remedied using the free-running mode and the offset values offered to the operator.

In the latest software release, WASCA offers a new reconstruction algorithm based on zonal reconstruction, resulting in improved resolution of the wavefront images.

MultiSpot

This is the only aberrometer in our study that contains a bimorph mirror for the purpose of compensating the patient's accommodation in real time. The MultiSpot can also be used to simulate the ideal vision by compensating the patient's aberrations.

Other interesting features of this device are the possibility of recording short wavefront movies and the error map that shows the difference between the measured and the calculated spot pattern.

One disadvantage of the MultiSpot is that it might take the operator some time to learn how to use the device properly.

Allegretto

The Allegretto has an exceptionally elaborated alignment procedure, resulting in a highly accurate location of the pupil center. However, in case of elliptical pupil shapes, this estimation is sometimes displaced from the true center, and the alignment needs to be done manually. Also, the source intensity can be difficult to adjust depending on the installed camera.

This aberrometer is characterized by a long list of available options for fine-tuning the measurements and data representation that are interesting for wavefront research. Because of the large number of options, some training is required to operate the Allegretto to its full potential.

Conclusion

When choosing an aberrometer, it is important to keep in mind the purpose it will serve in daily clinical practice. If the aim is to use it as an extended corneal topographer, many of the options in the more elaborate systems are useless. These same options could, however, be helpful for clinical studies. Either way, in our opinion, there are a number of minimal requirements the aberrometers procedure should meet:

- A highly accurate alignment procedure
- A source wavelength in the middle of the visual range or a numerical compensation of the chromatic aberrations
- An averaging over several measurements
- An automatic test of the measurement quality
- An inhibition procedure for accommodation

These parameters should be considered at least equally important as data assessment parameters, such as the number of samples and Zernike polynomials and the dioptric range of the prefocus. Most of the aberrometers in this study did not provide all of these features.

Besides the common parameters offered by each aberrometer, such as the refraction values, the total and higher-order wavefronts, the total and higher-order RMS values, and the Zernike coefficient values, the minimal data representations should be the following:

- An error estimate map
- A refraction map
- PSF
- MTF
- A graph of refraction versus pupil size (including an error estimate on the refraction)

Furthermore, depiction of the raw data can be useful in some cases, as can a simulated visual acuity map. The Zernike notation details and the data export functions are only interesting when the numerical data are used for comparative studies using data from different wavefront devices.

We did not determine the consistency of the measurements given by these aberrometers in terms of refraction and wavefront aberrations. This is addressed in the second part of this article.

References

1. Molebny V, Pallikaris IG, Naoumidis LP, et al. Retina ray-tracing technique for eye refraction mapping. SPIE Proc 1997; 2971:175–183
2. Navarro R, Moreno-Barriuso E. Laser ray-tracing method for optical testing. Opt Lett 1999; 24:951–953
3. Liang J, Grimm B, Goelz S, Bille JF. Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. J Opt Soc Am A 1994; 7:1949–1957
4. Thibos LN. Principles of Hartmann-Shack aberrometry. J Refract Surg 2000; 16:S563–S565
5. Mrochen M, Kaemmerer M, Mierdel P, et al. Principles of Tscherning aberrometry. J Refract Surg 2000; 16: S570–S571
6. MacRae S, Fujieda M. Slit skiascopic-guided ablation using the Nidek laser. J Refract Surg 2000; 16:S576–S580
7. Pettit GH. How Alcon/Summit/Autonomous answers important questions about their customized laser platform. J Refract Surg 2001; 17:S613–S615

8. Mrochen M. Revealing company secrets—please tell the truth and nothing but the truth! J Refract Surg 2002; 18:S644–S651
9. Larichev A, Ivanov PV, Iroshnikov NG, Shmalhauzen VI. Measurement of eye aberrations in a speckle field. Quantum Electronics 2001; 12:1108–1112
10. Webb RJ, Penney CM, Thompson KP. Measurement of ocular local wavefront distortion with a spatially resolved refractometer. Appl Opt 1992; 31:3678–3686
11. Tscherning M. Die monochromatischen Aberrationen des menschlichen Auges. Z. Physiologischen Psychol Sinnesorg 1894; 6:456–471
12. Applegate R, Thibos LN, Bradley A, et al. Reference axis selection: subcommittee report of the OSA working group to establish standards for measurement and reporting of optical aberrations of the eye. J Refract Surg 2000; 16:S656–S658
13. Schwiegerling J. Scaling Zernike expansion coefficients to different pupil sizes. J Opt Soc Am A Optics Image Sci Vis 2002; 19:1937–1945
14. Thibos L, Applegate RA, Schwiegerling J, Webb R. Standards for reporting the optical aberrations of the eyes. In: OSA Trends in Optics and Photonics. Vision Science and Its Applications. Washington, DC, Optical Society of America, 2000, 35, 232–244