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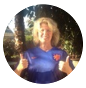

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Evaluation of a clinical aberrometer for lower-order accuracy and repeatability, higher-order repeatability, and instrument myopia

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Background: Refractive surgery has stimulated the development of aberrometers, which are instruments that measure higher-order aberrations. The purpose of this study was to test one clinical aberrometer, the Complete Ophthalmic Analysis System (COAS), for its accuracy, repeatability, and instrument myopia for measuring sphere and astigmatism and its repeatability for measuring higher-order aberrations.

Methods: Aberrations of 56 normal eyes (28 subjects) were measured with and without cycloplegia using a COAS, a conventional autorefractor and by subjective refraction. We evaluated lower-order accuracy (sphere and astigmatism) of the COAS and autorefractor by comparing that data with that of subjective refraction. We also tested COAS lower- and higher-order repeatability for 5 measurements taken in less than 1 minute. We evaluated instrument myopia by comparing cycloplegic and noncycloplegic measurements of the same eye. Data were analyzed for a 5.0-mm-diameter pupil.

Results: Mean COAS spherical error was between −0.1 and +0.4 diopters (D), depending on cycloplegia and the kind of sphere power computation selected. Cylinder power errors were less than 0.1 D. COAS repeatability coefficients were better than 0.25 D, and instrument myopia was less than 0.4 D. These were comparable with those of autorefraction. Higher-order repeatability was sufficient to allow reliable measurement of normal third-order aberrations and spherical aberration.

Conclusions: Accuracy, repeatability, and instrument myopia of the COAS are similar to those of a conventional autorefractor. Accuracy and repeatability are also similar to those of subjective refraction. Like an autorefractor, the COAS provides instantaneous, objective measurements of sphere and astigmatism, but it also measures higher-order aberrations. We found that it is capable of reliably measuring problematic higher-order aberrations and is therefore a valuable asset for modern clinical eye care.

Key Words: Aberrations, aberrometer, aberrometry, wavefront, refractive errors, accuracy, repeatability, instrument myopia

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Background

Context of the study

Until recently, the clinical measurement and correction of refractive errors was limited to sphere and astigmatism, whereas more complicated refractive errors, known as *higher-order aberrations*, were ignored. For most patients, higher-order aberrations had little effect on vision, and they were too difficult to measure or correct. This changed with the advent of refractive surgery, which was designed originally to correct sphere and, more recently, astigmatism, but in many cases inadvertently created large higher-order aberrations that caused poor vision.[1,2] These unwanted aberrations were troublesome particularly for patients with small treatment zones, higher prescriptions, or large pupils.[3–9] The new wavefront-guided laser *in situ* keratomileusis (LASIK) procedures are designed to minimize higher-order aberrations. The popularity of refractive surgery raised a number of concerns for Army aviation. Should the Army accept pilot candidates who have had refractive surgery? Even if sphere and astigmatism were corrected, could higher-order aberrations affect flight performance? Should the Army establish new visual or optical standards for pilots who have had refractive surgery? As part of a larger study to answer these questions, we evaluated the instrument we would use to measure aberrations: the Complete Ophthalmic Analysis System (COAS) aberrometer.

Aberrometers

Aberrometers are instruments that measure optical aberrations. In the 1970s, Roland Shack developed what is now known as the Shack-Hartmann (SH) aberrometer,[10] which has been used by astronomers to dramatically improve telescope images.[11] Junzhong Liang first applied SH aberrometry to the human eye in about 1990,[12] and within a decade vision scientists around the world had adopted this as the preferred technique for measuring ocular aberra-

Figure 1 The COAS manufactured by Wavefront Sciences, Inc., one of the first commercial ophthalmic aberrometers.

tions.[13–26] In 2001, WaveFront Science, Inc, (Albuquerque, NM) introduced the first commercial ophthalmic SH aberrometer, the COAS (*see* Figure 1). Other technologies for measuring the eye's higher-order aberrations, include Tscherning and Howland aberroscopy, laser ray tracing, spatially resolved refractometry, and slit-scan retinoscopy.[27] SH-type aberrometers, however, are the most popular because of their high-resolution measurements, known laboratory accuracy,[28] and mechanical simplicity.

Specifying ocular aberrations

Aberrometers measure aberrations of the eye by recording the path taken by light rays passing through the pupil.[29] In SH aberrometry, light is reflected off the retina and measured as it passes out through the eye's optics (*see* Figure 2A and B). A camera captures the light emitted from the eye and records an image of the pupil filled with a pattern of dots (*see* Figure 2C). By analyzing the position of each dot, the instrument computes the path of each ray and reconstructs the optical wavefront formed by the eye. By analyzing the wavefront's shape, all of its refractive errors, including sphere, astigmatism, and higher-order aberrations can be completely identified. In an eye with perfect optics, the wavefront of light emitted from the eye would be perfectly flat (*see* Figure 2A), but if the eye contains any aberrations, they will distort the wavefront according to the type and magnitude of aberrations present (*see* Figure 2B). The goal of aberrometry is to measure the wavefront formed by the eye's optics; therefore, aberrometers are sometimes called *wavefront sensors*.

Most eyes produce a wavefront that has a complex, irregular shape formed by the combined effects of multiple aberrations, but by mathematical analysis, aberrations which are present can be determined. This can be done by fitting the wavefront to an algebraic equation such as the polynomials developed by Frits Zernike in 1934.[30] Zernike polynomials, as defined by the Optical Society of America[31,32] and the American National Standards Institute,[33,34] are the accepted system for recording ocular higher-order aberrations. A Zernike polynomial can contain an infinite number of terms, each representing a discrete aberration, but a limited number of terms is usually sufficient to represent the aberrations in an eye.[13,14,35] The individual aberrations are sometimes referred to as Zernike modes, and they are organized into a hierarchy of Zernike orders.[31] This allows each mode (aberration) to be numerically identified by a subscript, which tells its order, and a positive or negative superscript, which designates the mode within that order. For example, the mode labeled Z_3^{-1} is the third-order aberration, vertical coma.

Study objectives

The principles of Shack-Hartmann (SH) aberrometry are well established, and laboratory devices have proven reliable.[15,19,20,28] However, relatively little work has been published on the accuracy of the new clinical aberrometers.[26,28,36] Our objectives were to evaluate the COAS in terms of its (1) accuracy, (2) repeatability, and (3) instrument myopia for a normal population of Army flight school applicants. Accuracy describes how correctly an instrument measures what it is supposed to measure. We evaluated accuracy for lower-order aberrations

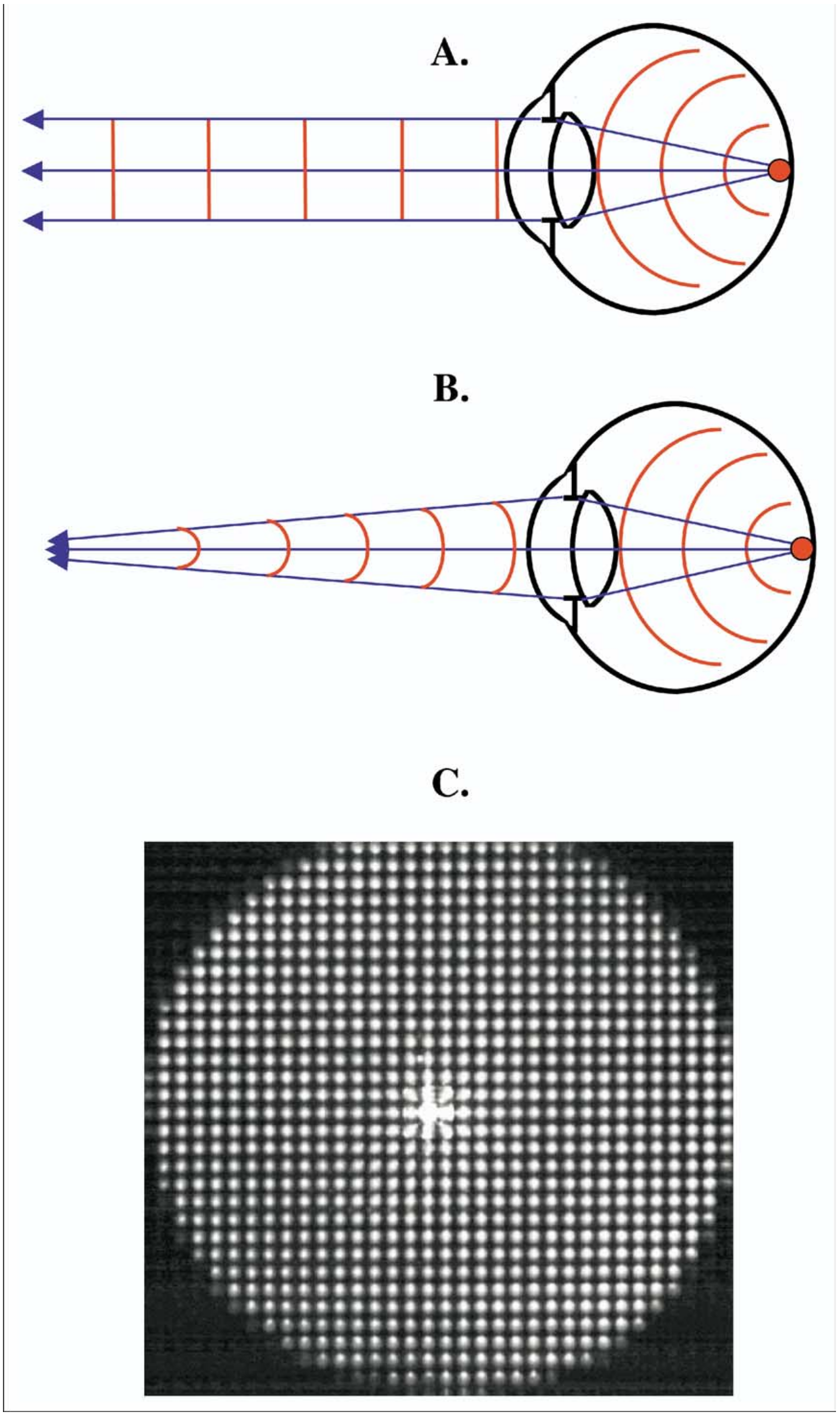

Figure 2 Shack-Hartmann aberrometers measure optical quality of the eye by projecting a point onto the retina and measuring the wavefront of light emitted from the eye. In an eye with perfect optics, a flat wavefront emerges (***A***). Aberrations such as simple myopia (***B***) bend and distort the wavefront. The raw data image recorded by a Shack-Hartmann aberrometer is an array of spots in the pupil (***C***). By analyzing the position of the spots, we can reconstruct the wavefront emitted from the eye.

only (sphere and astigmatism), by comparing COAS measurements to subjective refraction. Repeatability describes measurement consistency. We assessed repeatability for both lower- (sphere and astigmatism) and higher-order aberrations by making multiple measurements and computing statistics related to the variance. We also measured instrument myopia, which is the tendency of the eye to overaccommodate when looking into tabletop instruments.

Methods

Subjects

We recruited 28 volunteers from among pilot candidates who were undergoing a physical examination for entry into Army aviation school. Inclusion criteria included the vision and ocular health requirements for flight school stated in Army Regulation AR 40-501:

- Spherical refractive error between –0.75 diopters (D) and +3.00 D
- Astigmatism ≤ 0.75 D
- Uncorrected visual acuity of 20/50 or better in each eye
- Best corrected visual acuity of 20/20 or better in each eye
- No evidence of ocular disease

In addition, subjects must not have worn rigid contact lenses within 6 months, never have had refractive surgery, and have no medical contraindications to the use of cycloplegic or anesthetic eye drops. One female and 27 male subjects, with a mean age of 24.7 ± 3.3 years, volunteered. The mean noncycloplegic refractive error was +0.30 ± 0.41 D sphere and –0.21 ± 0.26 D cylinder. Cycloplegia shifted the mean subjective refraction +0.25 D sphere and 0.09 D cylinder.

Procedures

The investigators briefed subjects on the study's purpose, duration, procedures and their rights as subjects. Subjects provided informed consent as required by the US Army Aeromedical Research Laboratory's Human Use Committee. The raw data for our study were provided by autorefraction, subjective refraction, and aberrometry done in the following order:

Noncycloplegic refractions
- Auto-refraction (3 measurements with the Nidek ARK-700A in < 1 minute)
- Subjective refraction (1 measurement)
- Aberrometry (5 measurements with the COAS in < 1 minute)

Cycloplegic refractions (2 drops of 1% cyclopentolate)
- Aberrometry (5 measurements in < 1 minute)
- Subjective refraction (1 measurement)
- Auto-refraction (3 measurements in < 1 minute)

The COAS aberrometer was configured to report aberrations for a 5-mm-diameter pupil up to the eighth Zernike order (44 modes). Measurements were made with dim room illumination, and after each measurement, sphere, cylinder, axis, pupil diameter, and Zernike coefficients were saved in a database for subsequent analysis. We measured right and left eyes, but analyzed them separately.

Accuracy

Ideally, accuracy testing requires that we know the true value to be measured. We had no way to absolutely know each eye's aberrations, but we used the subjective refraction as our best estimate of the lower-order aberrations, sphere, and astigmatism. Because we had no way to know the higher-order aberrations, we could not evaluate higher-order *accuracy*, although we did evaluate higher-order *repeatability*. Our approach to testing lower-order accuracy was to see how much the COAS sphere and astigmatism differed from the subjective refraction.

The following steps summarize data processing for the accuracy assessment.[26]

- Convert each subjective and COAS refraction (sphere, cylinder, axis) to a power vector. This was necessary because astigmatic data with dissimilar axes cannot be added together directly. Power vectors can be added directly, which makes it possible to compute differences, means, and variances. The sphere (S), cylinder (C), and axis (θ) may be converted to power vector [J_{45}, M, J_{180}] according to Equations 1-3. The J_{180} term used in this paper is the same as the J_0 term in Thibos' paper on power vectors.[37]

$$J_{45} = (-C/2)\sin(2\theta) \tag{1}$$

$$M = S + C/2 \tag{2}$$

$$J_{180} = (-C/2)\cos(2\theta) \tag{3}$$

- Compute the mean COAS power vector (vector C) for each eye by averaging the J_{45}, M, and J_{180} for the five COAS refractions.
- Find the COAS refraction error (vector E) for each eye by taking the difference between the mean COAS power vector (vector C) and the subjective refraction (vector S), according to Equation 4.

$$\vec{E} = \vec{C} - \vec{S} \tag{4}$$

- Compute the overall mean COAS error by averaging vector E across 28 subjects.
- To simplify interpretation, we converted the mean COAS error vector to the equivalent sphere, cylinder and axis using Equations 5 through 7.

$$C = -2\sqrt{J_{45}^2 + J_{180}^2} \tag{5}$$

$$S = M - C/2 \tag{6}$$

$$\theta = [\tan^{-1}(J_{45}/J_{180})]/2 \tag{7}$$

Computation of the axis required an additional step to ensure that it conformed to standard minus-cylinder notation ($0 > \theta \leq 180$ degrees). We corrected the axis value based on the initial result for θ (Equation 7) and the logical tests below.

IF $J_{180} < 0$, axis = $\theta + 90$
IF $J_{180} = 0$ AND IF $J_{45} < 0$, axis = 135
IF $J_{180} = 0$ AND IF $J_{45} > 0$, axis = 45
IF $J_{180} > 0$ AND IF $J_{45} \leq 0$, axis = $\theta + 180$
IF $J_{180} > 0$ AND IF $J_{45} > 0$, axis = θ

- We also summarized the COAS error in vector E by combining the 3 numbers J_{45}, M, and J_{180} into a single magnitude value (m) according to Equation 8. This is similar to the clinical practice of simplifying spherocylindrical errors with the spherical equivalent. We did this for each eye, and found the mean across 28 eyes.

$$m = \sqrt{J_{45}^2 + M^2 + J_{180}^2} \tag{8}$$

By default, the COAS computes sphere power based on the value of mode Z_2^0 (defocus), but it offers an alternate computation referred to as the *Seidel sphere*. It includes mode Z_4^0 (spherical aberration) in the calculation and may better match the way a human eye responds to a subjective refraction. A complete description of how the COAS computes both the default and Seidel spheres may be found in another article.[26] We tested COAS accuracy for both the default and the Seidel sphere. For comparison, we also tested accuracy of the autorefractor following the procedures outlined above. Accuracy was analyzed separately for right and left eyes with and without cycloplegia.

Repeatability for lower-order aberrations (sphere and astigmatism)

Because 5 COAS measurements were made of each eye by the same investigator, we were able to evaluate repeatability, which we did for both lower- (sphere and astigmatism) and higher-order aberrations. Repeatability testing for lower-order aberrations made use of both the default and Seidel spheres and evaluated right and left eyes, with and without cycloplegia separately. Autorefractor repeatability was computed in the same manner, except that 3 measurements were taken of each eye. We processed lower-order data for each eye as follows:

- Convert each of the 5 COAS refractions (sphere, cylinder, axis) to a power vector (Equations 1-3).
- Compute the mean COAS refraction as the mean of the 5 original power vectors.
- Subtract the mean from each of the 5 original power vectors. This gave 5 difference vectors.
- Compute the magnitude (Equation 8) of each difference vector and the mean of these 5 magnitudes. This gave the mean deviation, in diopters, for each eye.
- Square and sum the mean deviations for 28 eyes and divide by 28 to obtain the RMS (root mean squared) deviation.
- Compute a repeatability coefficient, defined as the RMS deviation multiplied by 1.96. This follows the method developed by Bland and Altman[38] and used in other clinical studies[39-41] to evaluate repeatability of diagnostic instruments.

Repeatability for higher-order aberrations

Aberrometers record higher-order aberrations by using a numerical coefficient for each of the Zernike modes. Each Zernike coefficient tells the magnitude (positive or negative) of the aberration. For normal eyes, the most significant higher-order aberrations are contained in the third and fourth Zernike orders. Aberrations in the fifth and higher orders are normally much smaller and have little effect on vision.[24] For the sake of completeness, we evaluated aberrations well beyond this—through the eighth order, which includes 39 higher-order modes. We measured each eye's aberrations with the COAS 5 times. From the 5 measurements for each mode, we computed a standard deviation (SD), standard error ($SE = SD/\sqrt{5}$) and 95% confidence interval ($CI = SE \bullet 2.78$), then averaged the confidence intervals across 28 eyes. The mean 95% CIs for these aberrations were interpreted as a measure of instrument noise and used as our

Table 1. COAS Error for measuring sphere and cylinder for right (O.D.) and left (O.S.) eyes, without and with cycloplegia, using the default and Seidel sphere (mean ± 1 SD).

Eye/condition	Sphere type	Sphere error (D)	Cylinder error (D)	Vector magnitude (D)
O.D./no cyclo	Default	−0.10 ± 0.60	−0.09 ± 0.27	**0.43** ± 0.25
O.S./no cyclo	Default	−0.14 ± 0.64	−0.07 ± 0.34	**0.43** ± 0.30
O.D./no cyclo	Seidel	+0.08 ± 0.55	−0.09 ± 0.27	**0.38** ± 0.22
O.S./no cyclo	Seidel	+0.08 ± 0.64	−0.07 ± 0.34	**0.43** ± 0.24
O.D./cyclo	Default	+0.14 ± 0.42	−0.08 ± 0.31	**0.29** ± 0.14
O.S./cyclo	Default	+0.11 ± 0.46	−0.09 ± 0.32	**0.29** ± 0.20
O.D./cyclo	Seidel	+0.44 ± 0.42	−0.08 ± 0.30	**0.45** ± 0.24
O.S./cyclo	Seidel	+0.41 ± 0.40	−0.09 ± 0.32	**0.41** ± 0.22

Note: A negative sphere error indicates that the instrument overestimated myopia; a positive error indicates hyperopic error. The last column shows the mean error in terms of power vector magnitude (bold). Analysis pupil diameter was 5.0 mm.

summary statistic for higher-order repeatability of the COAS. This process was applied separately to right and left eyes, with and without cycloplegia.

Instrument myopia

We computed instrument myopia for the COAS and autorefractor by the following steps[26]:

- Cycloplegia may have induced a slight change in the true refraction, so for each eye we computed the change (vector Δ) as the difference between the subjective noncycloplegic (vector S_m) and subjective cycloplegic (vector S_c) power vectors (Equation 9).

$$\vec{\Delta}=\vec{S}_m-\vec{S}_c \tag{9}$$

Instrument myopia (vector I in Equation 10) for each eye was defined as the difference between the COAS noncycloplegic (vector C_m) and COAS cycloplegic (vector C_c) power vectors minus the true change, vector Δ.

$$\vec{I}=\vec{C}_m-\vec{C}_c-\vec{\Delta} \tag{10}$$

The mean of all COAS instrument myopia values was computed for right and left eyes for the default and Seidel spheres. Mean instrument myopia power vectors were converted to sphere, cylinder, and axis and the mean spherical equivalent.

Results

Accuracy

Accuracy for measuring sphere and astigmatism is summarized in Table 1 for the COAS and in Table 2 for the autorefractor. The error vector magnitudes (Table 1, right column, bold) provide the simplest way to describe COAS accuracy for sphere and astigmatism. All rows showed errors less than 0.5 D, which is similar to the range of error seen with the autorefractor (*see* Table 2). Smallest COAS error was found with cycloplegia and the default sphere (about 0.3 D). Otherwise, without cycloplegia, power vector error using either the default or Seidel sphere was about 0.4 D. For all conditions except one (cycloplegia, Seidel sphere), the mean error for measuring sphere (*see* Table 1, column 3) only was approximately ±0.1 D. The Seidel sphere shifted the spherical error about +0.25 D for a 5.0-mm-diameter pupil. For all rows, cylinder error (*see* Table 1, column 4) was less than −0.1 D.

Figure 3 shows the magnitude of COAS vector errors for each eye across a range of refractive errors (right, left, default, and Seidel spheres) when no cycloplegia was used. For both the default sphere (large symbols) and Seidel sphere (small symbols), approximately 80% of the errors were less than 0.6 D. In a few cases, magnitudes exceeded 1.0 D. The Seidel sphere resulted in fewer extreme errors, so that none exceeded 0.9 D. Figure 4 shows a similar plot when cycloplegia was used. The distribution of errors was

Table 2. Mean autorefractor (Nidek ARK-700A) error for sphere and cylinder for right (O.D.) and left (O.S.) eyes, with and without cycloplegia

Eye/condition	Sphere error (D)	Cylinder error (D)	Vector magnitude (D)
O.D./no cyclo	+0.29	−0.15	**0.40**
O.S./no cyclo	+0.28	−0.12	**0.41**
O.D./cyclo	+0.46	−0.09	**0.47**
O.S./cyclo	+0.43	−0.05	**0.47**

Note: A negative sphere error indicates the instrument overestimated myopia; a positive error indicates hyperopic error. The last column shows the mean error in terms of power vector magnitude (bold). The autorefractor measured across a 3.5-mm diameter pupil.

concentrated closer to zero, with approximately 90% of the errors less than 0.6 D. In this case, fewer outliers were seen when the default sphere was used. For comparison, Figure 5 shows a similar analysis for the autorefractor. The distribution of errors is marginally better than the COAS without cycloplegia and marginally worse than the COAS with cycloplegia. Cycloplegia did not significantly improve the error distribution for the autorefractor. About 80% of the errors were less than 0.6 D. The autorefractor measured across a 3.5-mm-diameter pupil.

Repeatability

Table 3 shows mean COAS repeatability coefficients for right and left eyes, with and without cycloplegia, using the default and Seidel sphere. In all cases it was less than 0.25 D. COAS repeatability was marginally better with the default sphere and cycloplegia. For comparison, the autorefractor's repeatability coefficients (*see* Table 3, right column) were about 0.1 D smaller than that of the COAS.

Figure 6 shows COAS repeatability for higher-order aberrations. Data points indicate repeatability in terms of the mean 95% CIs for each eye/condition for each mode. Approximately 90% of the points fall within the shaded region, which generalizes mode-by-mode repeatability based on these results. That is, COAS repeatability for each mode is indicated by the height of the shaded regions (in micrometers), which declines in each successive order. The respective values for the third, fourth, fifth, sixth, and sevenths orders are 0.035, 0.025, 0.02, 0.015 and 0.010 μm. Eighth-order values (not shown) were similar to those in the seventh order. These values can be interpreted as our estimate of measurement noise; that is, variability caused by the instrument or measurement procedure.

Instrument myopia

Instrument myopia had little effect on astigmatism (< 0.1 D change in each case), so we summarized instrument myopia in terms of the spherical equivalent power (*see* Table 4). COAS instrument myopia was smaller when the default sphere was used, about −0.25 D. For comparison, instrument myopia with the autorefractor was about −0.2 D.

Discussion

Aberrometers, such as the COAS, provide the only means for measuring higher-order aberrations in a clinical setting and the COAS was the instrument chosen by our laboratory to study the ocular aberrations of Army pilots. Before doctors can depend on the data provided by aberrometers, they need to know how reliable these instruments are. Because aberrometers measure lower-order aberrations as well, they can also function as autorefractors. We assessed COAS accuracy, repeatability, and instrument myopia for lower-order aberrations and only repeatability for higher-order aberrations. All COAS analyses were done for a 5.0-mm-diameter pupil.

Accuracy

We expressed accuracy for measuring the combined lower-order aberrations of sphere and

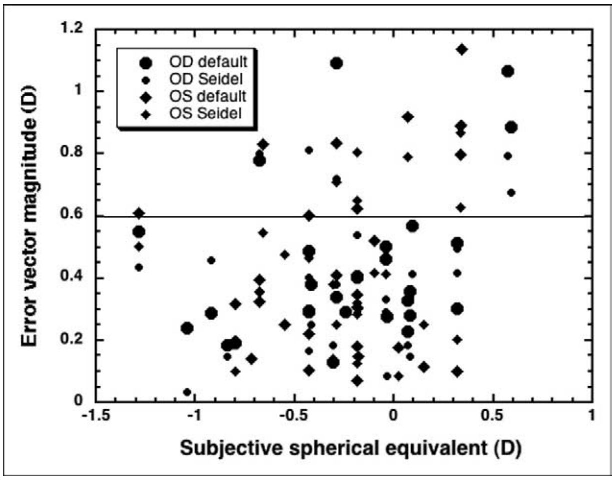

Figure 3 Magnitude of COAS vector errors across a range of refractive errors without cycloplegia. All units are in diopters. Approximately 80% of the errors, using both the default (large symbols) and Seidel spheres (small symbols) are within 0.60 D.

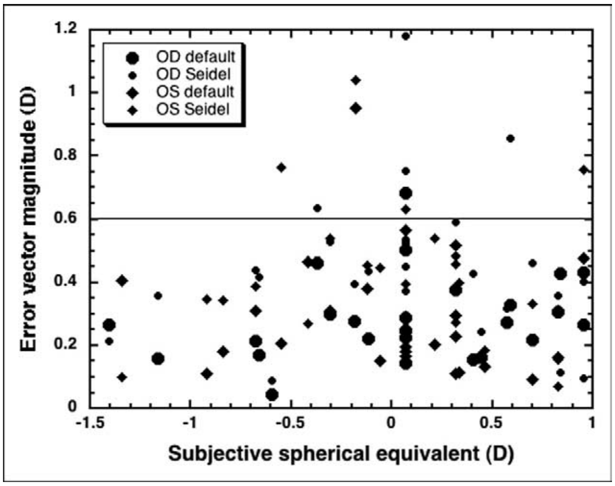

Figure 4 Magnitude of COAS vector errors across a range of refractive errors with cycloplegia. All units are in D. Approximately 90% of the errors, using both the default sphere (large symbols) and Seidel sphere (small symbols) are within 0.60 D.

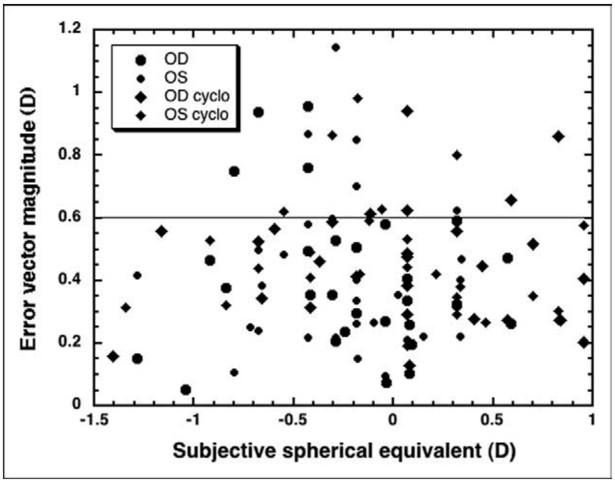

Figure 5 Magnitude of autorefractor vector errors across a range of refractive errors for the right and left eyes without (circles) and with (diamonds) cycloplegia. All units are in diopters. Without cycloplegia, 84% of the errors were less than 0.60 D. With cycloplegia, about 80% of the errors were less than 0.60 D.

astigmatism by the magnitude of the mean error vector. COAS accuracy was best with the default sphere and cycloplegia—0.3 D by this statistic. The autorefractor's accuracy was 0.4 D. To put this into perspective, a 0.3-D error vector magnitude is equivalent to a 1/8-D error in both the sphere and cylinder combined with a 12-degree axis error. Thus, we found that, on average, the COAS was capable of the same level of accuracy we can expect for a good subjective refraction. In some cases, however, COAS and autorefractor error vector magnitudes exceeded 1.0 D (*see* Figures 3 through 5), which is equivalent to a 0.5-D error in both the sphere and cylinder with a 30-degree axis error. Our results with human eyes were only marginally worse than the reported accuracy of the COAS with model eyes. Cheng et al[28] reported mean errors of ±0.1 D sphere, ±0.1D cylinder and ±2° axis (equivalent to a 0.16-D vector error) across a broad range of refractive errors (−4.00 to +3.00) on model eyes. Accuracy declined slightly for greater refractive errors in that study.

There is still debate among vision scientists about how to best estimate the subjective sphere from aberrometer data. The COAS default setting computes the sphere directly from the second-order aberration Z_2^0 (defocus), whereas the Seidel sphere option takes into account the fourth-order aberration Z_4^0 (spherical aberration).[26] Some scientists believe that the Seidel sphere should give a better estimate of the subjective sphere, especially with large pupils. When no cycloplegia was used, we did not find better accuracy with the Seidel sphere. With cycloplegia it was marginally worse than with the default sphere. It is possible that our pupil diameters (5.0 mm) were not large enough to benefit from the Seidel computation, because, in another study, we found slightly better accuracy in larger pupils with the Seidel sphere.[26] It appears, therefore, that users should normally leave the default sphere setting in place and

Table 3. Repeatability coefficients for the COAS for default and Seidel spheres and for autorefraction

Eye/condition	COAS default sphere (D)	COAS Seidel sphere (D)	Autorefractor (D)
O.D./ no cyclo	0.20	0.24	0.12
O.S./ no cyclo	0.18	0.23	0.20
O.D./ cyclo	0.12	0.18	0.08
O.S./ cyclo	0.18	0.22	0.09

Note: Analysis pupil diameters were 5.0 mm for the COAS and 3.5 mm for the autorefractor.

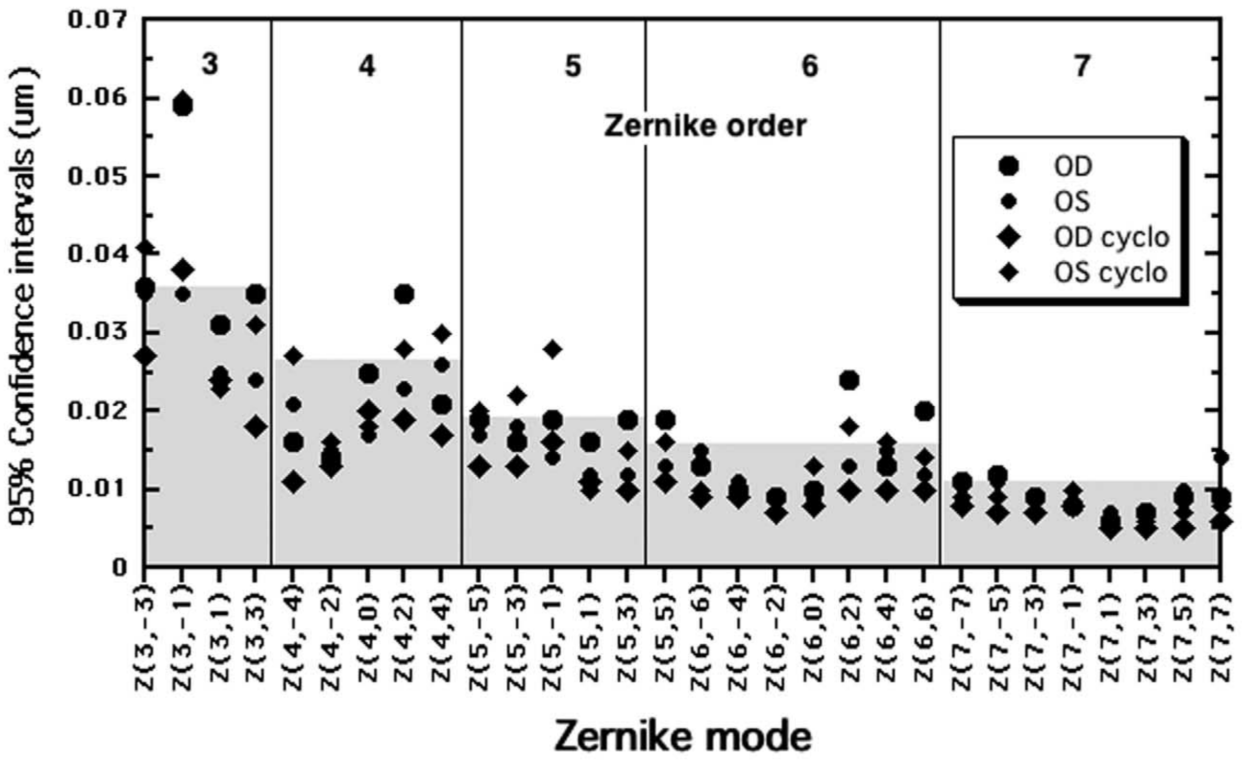

Figure 6 Repeatability of the COAS for measuring higher-order aberrations, expressed as 95% CI for 5 readings taken within 1 minute for right (O.D.) and left (O.S.) eyes, without and with cycloplegia. Each data point represents the mean for 28 eyes (27 for O.S. cyclo). The shaded region contains 90% of the data points and indicates a generalized estimate of instrument noise for each mode. Pupil diameter was 5.0 mm.

reserve the Seidel option for widely dilated (>6 mm) pupils.

As mentioned in the Methods section, we were not able to evaluate accuracy for higher-order aberrations in this study. Cheng et al[28] were able to evaluate COAS accuracy for some higher-order modes using model eyes, for which the higher-order aberrations could be computed by ray-tracing. They found mean errors of less than 0.01 μm for Z_4^0 (spherical aberration), less than 0.03 for Z_3^1 (coma) and ≤ 0.3 μm for Z_4^2 (5.0-mm pupil). These correspond to the respective equivalent diopter[24] values of 0.1, 0.3, and 0.3 D.

Repeatability

Repeatability refers to the variability of repeated measurements. The COAS repeatability coefficients for lower-order aberrations (<0.25 D) were similar to what we would expect from subjective refraction. For comparison, the following 5 refractions of the same eye would have a repeatability coefficient of 0.20 D:

Table 4. Instrument myopia, expressed as the change in spherical equivalent power, in diopters (mean ± 1 SD)

Instrument	Eye	Sphere method	Instrument myopia
COAS	O.D.	Default	−0.24 ± 0.42
COAS	O.S.	Default	−0.24 ± 0.35
COAS	O.D.	Seidel	−0.36 ± 0.43
COAS	O.S.	Seidel	−0.29 ± 0.41
Autorefractor	O.D.	NA	−0.19 ± 0.33
Autorefractor	O.S.	NA	−0.19 ± 0.37

Note: A negative value indicates that the instrument overestimated myopia.

- −1.00 – 1.25 × 180
- −1.00 – 0.75 × 180
- −1.00 – 1.00 × 170
- −1.25 – 1.00 × 180
- −0.75 – 1.00 × 180

Because COAS repeatability was marginally better with the default sphere (mean 0.17 D), we recommend using it rather than the Seidel sphere for most cases.

We also evaluated COAS repeatability for higher-order aberrations. Higher-order repeatability was generally the same with or without cycloplegia. As shown by the shaded region in Figure 6, it was approximately 0.035 μm (equivalent to 0.04 D) for third-order modes, 0.025 μm (0.03 D) for fourth-order modes, and declined to less than 0.02 μm (0.02 D) for the fifth order and above. These values are important to keep in mind when interpreting aberrometry, because Zernike coefficients less than the noise level are essentially immeasurable. For example, if the instrument reports −0.02 μm of mode Z_3^{-1} (vertical coma) aberrations, it cannot be assumed that the patient has any of this aberration, because it could just be caused by instrument noise. These results apply for a pupil diameter of 5.0 mm. Noise would probably increase with larger pupils and decrease with smaller pupils.

The variability that we measured for higher-order aberrations was only slightly worse than that reported in another study by Cheng et al.[36] In that study, they estimated that most of the variability of COAS was attributable to fluctuations in accommodation, the tear film, or eye position rather than to the instrument itself. The COAS may be subject to axial, transverse, or angular positioning errors, but they showed that, within the range of misalignments expected for normal clinical use, these caused no significant error.[28,36]

Instrument myopia

The COAS showed marginally more instrument myopia than the autorefractor (mean, 0.28 versus 0.19 D). We previously found almost no instrument myopia with the COAS, but all of those subjects were myopic.[26] The slightly greater instrument myopia in this study may have been caused by the inclusion of young hyperopes, who tend to habitually overaccommodate.

Conclusions

In normal eyes, higher-order aberrations are very small and have little effect on vision. The magnitudes of higher-order aberrations in normal eyes (averaged across several studies), for 5.0- and 6.0-mm pupils, are shown in Figure 7.[42] The figure also shows the noise range we determined for a 5.0-mm pupil, for which the most prominent aberrations—all third-order modes and fourth-order mode Z_4^0 (spherical aberration)—are measurable by the COAS because they exceed measurement noise (shaded zone). However, for a 5.0-mm pupil, the other fourth-order and fifth-order aberrations are so small that they do not exceed the noise limits and would, therefore, be difficult to measure. To detect the subtle aberrations in an eye with good optics, we, therefore, recommend measuring with as large a pupil as possible. Clinicians, however, are primarily interested in measuring abnormal aberrations, which would be larger than the values plotted in Figure 7. Based on this analysis, all problematic aberrations should be easily measurable with the COAS. This is particularly relevant to refractive surgery patients or others whose subnormal vision may be caused by poor optics.

In addition to its capacity to measure higher-order aberrations, the COAS can serve as an autorefractor by measuring sphere and astigmatism. Like a conventional autorefractor, it occa-

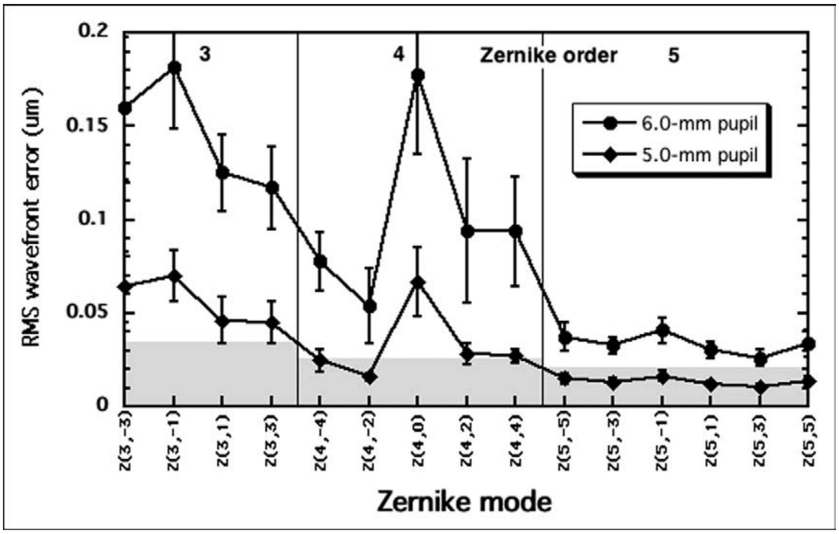

Figure 7 Magnitudes of higher-order aberrations expected for normal eyes for 5.0-mm and 6.0-mm-diameter pupils. Data were obtained by computing means from 5 studies that surveyed the aberrations of normal eyes over a range of refractive errors.

sionally has larger-than-average measurement errors, so when accuracy is critical, we recommend comparing COAS refractions to that obtained by a careful subjective refraction. We recommend using the default sphere, except for very large pupils. Cycloplegia slightly improves accuracy and repeatability for measuring sphere and astigmatism, but it would not be helpful in measuring the higher-order aberrations of a natural eye, because cycloplegia itself can change those aberrations.[43] We conclude that the COAS aberrometer provides clinicians with a fast, reliable, easy-to-use method to objectively measure lower- and higher-order aberrations of eyes.

Disclaimer

The opinions, interpretations, conclusions, and recommendations in this article are those of the authors and are not necessarily endorsed by the US Army and/or Department of Defense. None of the authors of this article have any financial interest in WaveFront Sciences, Inc., the manufacturer of the COAS.

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