

Normal-eye Zernike coefficients and root-mean-square wavefront errors

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PURPOSE: To compare aberrometry measurements from multiple sites and compute mean Zernike coefficients and root-mean-square (RMS) values for the entire data pool to serve as a reference set for normal, healthy adult eyes.

SETTING: Northeastern State University, Tahlequah, Oklahoma, USA.

METHODS: Data were collected from 10 laboratories that measured higher-order aberrations (HOAs) in normal, healthy adult eyes using Shack-Hartmann aberrometry (2560 eyes of 1433 subjects). Signed Zernike coefficients were scaled to pupil diameters of 6.0 mm, 5.0 mm, 4.0 mm, and 3.0 mm and corrected to a common wavelength of 550 nm. The mean signed and absolute Zernike coefficients across data sets were compared. Then, the following were computed: overall mean values for signed and absolute Zernike coefficients; polar Zernike magnitudes and RMS values for coma-like aberrations ($Z_3^{\pm 1}$ and $Z_5^{\pm 1}$ combined); spherical-like aberrations (Z_4^0 and Z_6^0 combined); and 3rd-, 4th-, 5th-, and 6th-order, and higher-order aberrations (orders 3 to 6).

RESULTS: The different data sets showed good agreement for Zernike coefficients values across most higher-order modes, with greater variability for Z_4^0 and Z_3^{-1} . The most prominent modes and their mean absolute values (6.0-mm pupil) were, respectively, Z_3^{-1} and 0.14 μm , Z_4^0 and 0.13 μm , and Z_3^{-3} and 0.11 μm . The mean total higher-order RMS was 0.33 μm .

CONCLUSIONS: There was a general consensus for the magnitude of HOAs expected in normal adult human eyes. At least 90% of the sample had aberrations less than double the mean values reported here. These values can serve as a set of reference norms.

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Shack-Hartmann aberrometry is the most popular method for measuring monochromatic higher-order aberrations (HOAs) of the eye. It provides objective, accurate,^{1–6} high-resolution data needed for wavefront-guided corrections and helps diagnose eyes with abnormal optics. Differential diagnosis of abnormal optics requires comparison with normative values, which may be known from clinical experience or by referring to published data. At least 6 major articles report Shack-Hartmann measurements for large populations of normal eyes.^{7–14} Our purposes were to (1) compare data from 10 laboratories and (2) compute the mean wavefront statistics that represent the consensus from these laboratories on the aberrations expected for a normal adult eye. Although aberrations may vary as a result of factors such as age, refractive error, and ethnicity, this study was limited to a survey of mean values computed without regard to trends among subgroups.

Aberrometers report the magnitude and sign of each HOA aberration by a string of Zernike coefficients, but

they apply for one pupil size and wavelength only.^{15–17} When the pupil size changes, those coefficients also change; however, given one set of coefficients, it is possible to mathematically compute their values for other pupil sizes.^{18–20} Most aberrometers measure with infrared light and then mathematically convert the Zernike coefficients to the corresponding values for a wavelength near the middle of the visible spectrum. The Materials and Methods section describes how these factors were addressed.

For most HOAs, positive and negative Zernike coefficients are approximately equally distributed in the population. Thus, on average, most higher-order Zernike coefficients have mean values close to zero. The exceptions are spherical aberration (mode Z_4^0), which usually has a mean positive value, and oblique trefoil (mode Z_3^{-3}), which usually has a mean negative value.^{8,10,12} Both positive and negative aberrations degrade image quality; therefore, when evaluating optical performance, we are primarily interested their magnitudes without regard to

sign. Thus, when describing the aberrations expected in a normal population of eyes, we should refer to the mean of absolute, rather than signed, Zernike coefficients.

Sometimes, the visual significance of HOAs can be better appreciated when similar paired modes are combined into polar modes characterized by a magnitude and axis.²¹ For example, it may be easier to understand the effects of modes Z_3^{-1} (vertical coma) and Z_3^1 (horizontal coma) when they are combined into a single polar mode, referred to simply as coma. The nine 3rd- and 4th-order modes can be combined into 4 polar modes (Z_{31} , Z_{33} , Z_{42} , Z_{44}) and 1 rotationally symmetric mode, spherical aberration (Z_{40}). In some cases, modes Z_3^{-1} , Z_3^1 , Z_5^{-1} , and Z_5^1 are combined and referred to as the coma-like aberrations. Similarly, Z_4^0 and Z_6^0 are sometimes combined and referred to as the spherical-like aberrations. The magnitude of combined Zernike modes may be computed by squaring each Zernike coefficient, summing them, and then taking the square root. This computes the root-mean-square (RMS) wavefront error for those modes combined and quantifies them as a group, with a single number. For example, we may be interested in knowing how large a patient's total HOA is or perhaps how large the 3rd- or 4th-order aberration is.

SUBJECTS AND METHODS

Since January 2000, more than 200 articles have reported Shack-Hartmann measurements of human eyes. Of them, ^{5,7,8,10,12,14} surveyed large populations of normal, healthy adult eyes that had not had refractive surgery for pupil diameters of at least 5.0 mm. The authors were contacted and copies of their data requested. The data consisted of pupil diameters and Zernike coefficients through the 5th or 6th Zernike order for each

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individual eye. In addition, data from our affiliated laboratories, the U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama; and the U.S. Navy Refractive Surgery Center, San Diego, California, were analyzed and scientists at several other laboratories known for visual optics research were contacted and their data requested.

Signed Zernike coefficients received from each laboratory were analyzed at their reported pupil diameters (6.0 mm for most eyes) and then rescaled for pupil diameters of 5.0 mm, 4.0 mm, and 3.0 mm using a MATLAB (The MathWorks, Inc.) script written by Campbell¹⁸ and based on principles presented by Schwiegerling.¹⁹ When scaling the coefficient for any particular mode, it is necessary to know the value of other modes as well and these differ from eye to eye. Because of this and because for many higher-order modes the mean of signed values tends toward zero, it was necessary to rescale Zernike coefficients to new pupil diameters eye by eye rather than using mean values from the different samples. Three hundred fifty-five eyes had pupil diameters smaller than 6.0 mm and were excluded from the 6.0-mm analysis. All eyes were used for analysis of 5.0 mm and smaller.

When the original data were reported for a wavelength other than 550 nm, they were converted to the 550-nm equivalent using the chromatic correction procedure described elsewhere.^{3,22} After the data were converted to common pupils sizes and a common wavelength, mean signed and absolute Zernike coefficients from the different laboratories were computed. Then, the overall means and standard deviations for the entire data pool for each Zernike mode and for pupil diameters of 6.0 mm, 5.0 mm, 4.0 mm, and 3.0 mm were computed.

The RMS wavefront error for polar Zernike modes, coma-like aberrations (Z_3^{-1} , Z_3^1 , Z_5^{-1} , Z_5^1 combined), spherical-like aberrations (Z_4^0 and Z_6^0 combined), and 3rd to 6th Zernike orders and total higher-order RMS (3 to 6 orders combined) were also computed. The RMS values were computed eye by eye, after which the mean RMS values for the entire data pool were computed.

RESULTS

Comparison Between Data Sets

Table 1 summarizes characteristics of the data sets included in the analysis. In total, data for 2560 normal adult eyes (1334 right eyes, 1226 left eyes) from 1433 subjects were accessed. The subjects included a range of ages, refractive errors, testing conditions, sexes, and nationalities, and a variety of Shack-Hartmann devices were used. The WaveScan (Visx) was used by 3 groups, which accounted for 1322 eyes, or 52% of the total data pool. Several other clinical aberrometers were used (COAS, WaveFront Sciences; Topcon; Zywave, Bausch & Lomb), and 4 sites used their own laboratory Shack-Hartmann devices.

Signed Zernike Coefficients

Figure 1 shows how the mean signed Zernike coefficients from the different data sets compared for a 5.0-mm pupil, the largest pupil size common to all eyes. Figure 1, top, shows results in right eyes and Figure 1, bottom, shows results in left eyes. The Houston study reported data for

Table 1. Summary of data sets used. Higher-order aberrations are through the 6th order with natural pupils, unless specified otherwise in comments.

Data Set	Number of Eyes OD/OS (Total)	Mean Age (y) \pm SD (Range)	Mean Sphere (D) \pm SD (Range)	Comment (Aberrometer Used)
Navy1	186/188 (374)	32.8 \pm 6.9	-3.21 \pm 1.54	Preop patients (WaveScan)
Navy2	207/209 (416)	30.6 \pm 4.8	0.09 \pm 0.59	Navy pilots (WaveScan)
Army*	47/47 (94)	29.9 \pm 7.6	-0.58 \pm 0.98	5.0 mm pupil, Army pilots (COAS)
Baylor*	283/249 (532)	41.3 \pm 10.2	-2.94 \pm 2.87	Preop patients (WaveScan)
Indiana*	100/100 (200)	26.1 \pm 5.6	-3.1 \pm 3	Cyclopentolate (laboratory device)
Houston*	67/0 (67)	24.8 \pm 4.2	-2.50 \pm 2.25	Phenylephrine (laboratory device)
Tokyo*	66/68 (134)	46.7 \pm 13.8	-2.40 \pm 2.98	Topcon
Rochester1*	109/109 (218)	40.8 \pm 10.6	-2.20 \pm 2.95	5.7 mm pupil (laboratory device)
Rochester2	160/154 (314)	33.1 \pm 8.2	-3.36 \pm 1.54	Zywave
Murcia (Spain)	89/82 (171)	26 \pm 6	-0.50 \pm 3.00	Laboratory device
Ohio State	20/20 (40)	24 \pm 5	-3.11 \pm 0.96	5.0 mm pupil (COAS)
Entire data pool	1334/1226 (2560)	33.8 \pm 7.8	-2.20 \pm 2.06	—

*Used in previously published studies

right eyes only. The most eyes were in the Baylor data set (283 right eyes; 249 left eyes). Except for 3 modes, Z_3^{-3} (oblique trefoil), Z_3^{-1} (vertical coma), and Z_4^0 (spherical aberration), most symbols clustered near zero. The mean and median values for these 3 modes were significantly different from zero by the 2-tailed Student *t* test ($\alpha < .01$) and the nonparametric sign test. For mode Z_3^{-3} (right eyes and left eyes), the Rochester study agreed with the others in magnitude but differed in sign. After this was discussed with the original investigator, the reason for this difference could not be determined; however, it was hypothesized that it may have been a result of differences in Zernike sign convention. The values for Z_4^0 showed greater spread and appeared to cluster in 2 subgroups, with mean values of approximately +0.04 μm and +0.09 μm (5.0-mm pupil). The differences between the 2 subgroups were highly significant ($P < .001$, *t* test). The other modes showed a more symmetric spread of data about the overall mean values. The 3 largest data sets (Navy1, Navy2, Baylor) showed close agreement across all modes. The greatest divergence was noted for Rochester1, Rochester2, and Tokyo, especially for mode Z_4^0 .

Absolute Zernike Coefficients

Figure 2, *top* and *bottom* (for right eyes and left eyes, respectively), shows the results for a 5.0-mm pupil in a format similar to that of Figure 1 for absolute Zernike coefficients. In terms of absolute value, the most prominent Zernike modes, in order, were Z_3^{-1} (vertical coma), Z_3^{-3} (oblique trefoil), Z_4^0 (spherical aberration), Z_3^1 (horizontal coma), and Z_3^3 (horizontal trefoil), all of which had mean values in the 0.05 to 0.08 μm range (5.0-mm pupil). The other higher modes showed mean values less than 0.03 μm , with declining values for higher orders. The greatest spread in mean absolute coefficients between the data sets was for

the 2 largest modes, Z_3^{-1} and Z_4^0 . In both modes, the largest values were in the Tokyo and Rochester2 data sets. Characteristics of the Tokyo data set that could have contributed to this trend were the inclusion of older subjects, perhaps ethnicity, and a clinical Shack-Hartman device unique to the data set. The Rochester2 data set was similar to most other data sets in mean age and refractive error but a Shack-Hartman device different from that used by the other groups. Except for Z_4^0 , all modes in the 4th order and above showed good agreement between data sets. For all modes, the largest 3 data sets (Navy1, Navy2, Baylor) showed close agreement.

Overall Pooled Mean Aberration Values

Absolute Zernike Coefficients

Table 2 shows the overall means and standard deviations for absolute Zernike coefficients pooled from all data sets for pupil diameters of 6.0 mm, 5.0 mm, 4.0 mm, and 3.0 mm. Because the mean values in right eyes and left eyes were similar, right eye and left eye absolute coefficients were combined. These results are shown graphically in Figure 3, *top* (6.0- and 5.0-mm pupil) and *bottom* (4.0- and 3.0-mm pupil), with the same ordinate ranges to facilitate comparison between pupil sizes. The standard deviations were equal to approximately 85% of each mean absolute value.

Polar Zernike Modes

Table 3 and Figure 4 show the overall mean polar Zernike magnitudes (right eyes and left eyes pooled) for pupil diameters of 6.0 mm, 5.0 mm, 4.0 mm, and 3.0 mm. The most prominent polar modes, in order, were Z_{31} (coma), Z_{33} (trefoil), and Z_{40} (spherical aberration), with respective mean values of 0.19 μm , 0.15 μm , and 0.13 μm for a 6.0-mm

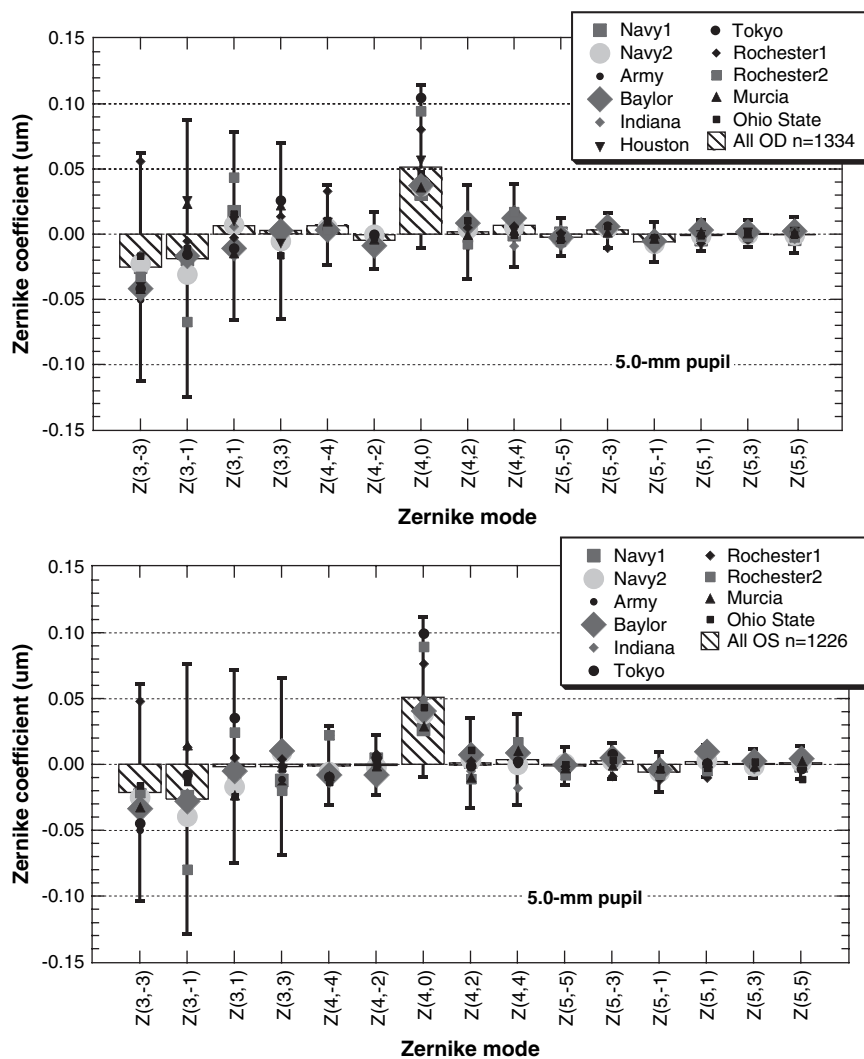


Figure 1. Signed Zernike coefficients for right eyes (top) and left eyes (bottom). Symbols indicate mean values from each data set. Symbol sizes indicate the relative number of eyes in each set. Striped boxes with error bars show means and standard deviations when all data are pooled.

pupil. The other higher-order modes showed a progressive decline. Standard deviations were about 70% of the respective mean values.

Root Mean Square for Combined Modes, Zernike Orders, and Total Higher-Order Aberrations

Table 3 also shows the mean RMS wavefront error values (right eyes and left eyes pooled) for coma-like aberrations (Z_3^{-1} , Z_3^1 , Z_5^{-1} , Z_5^1 combined), spherical-like aberrations (Z_4^0 and Z_6^0 combined), and 3rd- to 6th-order Zernike and total higher-order aberrations (orders 3 to 6). For a 6.0-mm pupil, the mean 3rd- and 4th-order RMS values were 0.25 μm and 0.17 μm , respectively, and the total higher-order RMS value was 0.33 μm . Figure 5 shows the change in higher-order RMS values as a function of pupil diameter. A 2nd-order polynomial curve

(equation 1) describes the relationship between pupil diameter in millimeters and total higher-order RMS values with a correlation coefficient $r = 0.9997$.

$$y = 0.02115x^2 - 0.09715x + 0.147 \quad (1)$$

The relationship can also be represented with the power function (equation 2) with a correlation coefficient $r = 0.9996$, if exponent $a = 2.8553$.

$$y = 0.0019249x^a \quad (2)$$

Distribution of Values

The distribution of signed and absolute 6.0-mm coefficients was studied by plotting histograms and testing for

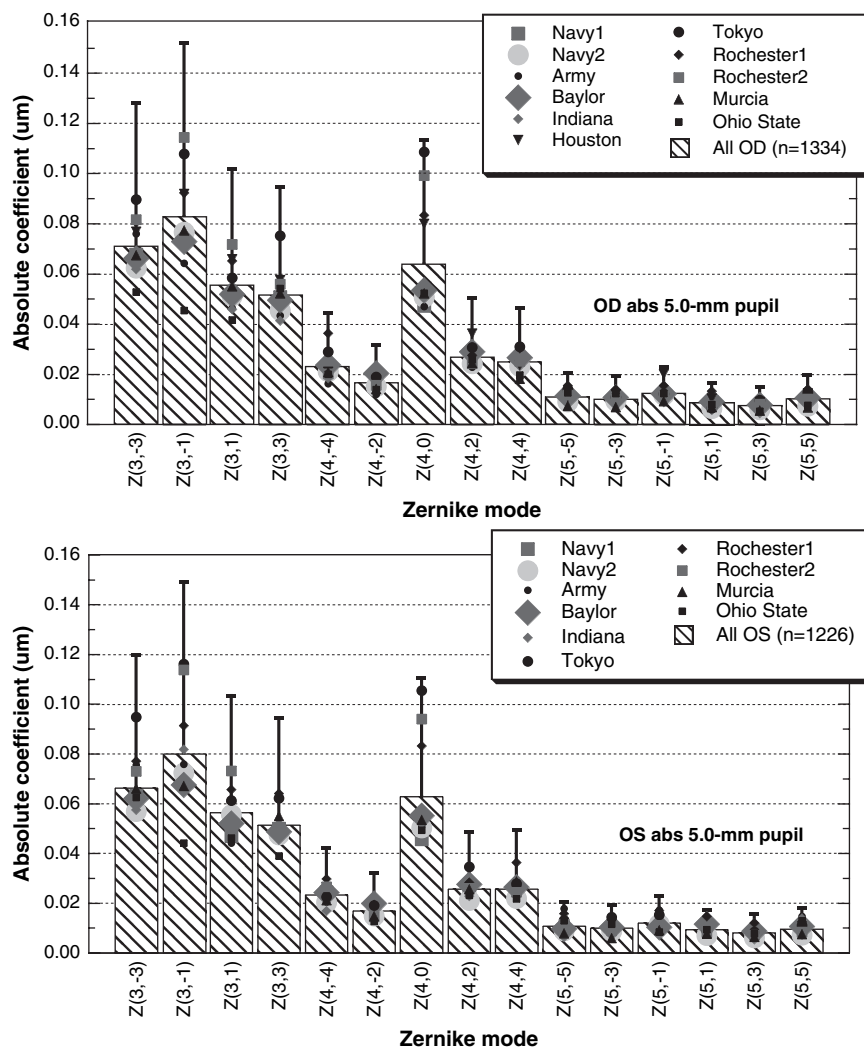


Figure 2. Absolute Zernike coefficients for right eyes (*top*) and left eyes (*bottom*). Symbols indicate mean values from each data set. Symbol sizes indicate the relative number of eyes in each set. Striped boxes with error bars show means and standard deviations when all data are pooled.

normality using the Shapiro-Wilk test. All signed coefficients showed bell-shaped distributions that were more peaked than a normal distribution. All modes failed the Shapiro-Wilk test, indicating that strictly speaking, they did not have normal distributions. For each Zernike mode in Table 2, approximately 86% of the sample population had absolute values less than or equal to the means plus 1 standard deviation. Approximately 96% had values less than or equal to the means plus 2 standard deviations. The same percentages applied to the distribution of RMS values listed in Table 3. Statistics such as those shown in Tables 2 and 3 can be used as reference norms to diagnose aberrometry measurements.

Another way to study the distribution of values is to normalize each absolute coefficient or RMS value by its mean, then plot the cumulative proportion of the sample

population with values less than the normalized value (Figures 6 to 8 for 6.0-mm data). For example each eye's 6.0-mm absolute coefficient for Z_3^{-3} was divided by 0.106 (Table 2, upper-left number) and plotted on Figure 6, which shows the population proportion with normalized absolute coefficients less than the x-axis values for all 3rd- and 4th-order modes. For all modes, approximately 60% of the sample population had absolute coefficient values less than the mean (normalized value 1.0), while about 90% had values less than double the mean (normalized value 2.0). Fifth- and 6th-order modes (not plotted) showed similar distributions. Figure 7 shows a similar plot for 3rd- through 5th-order polar modes. Approximately 60% of the sample population had polar magnitudes less than the means (normalized value 1.0), while approximately 93% of the population had magnitudes less than

Table 2. Mean absolute Zernike coefficients \pm 1 standard deviation (μm) for pooled data (right eyes and left eyes combined) for 4 pupil diameters.

Zernike Term	Pupil Diameter (mm)			
	6.0	5.0	4.0	3.0
Z_3^{-3}	0.106 \pm 0.088	0.069 \pm 0.056	0.040 \pm 0.033	0.019 \pm 0.016
Z_3^{-1}	0.143 \pm 0.118	0.082 \pm 0.069	0.045 \pm 0.038	0.021 \pm 0.018
Z_3^1	0.090 \pm 0.076	0.056 \pm 0.047	0.033 \pm 0.027	0.015 \pm 0.013
Z_3^3	0.081 \pm 0.066	0.052 \pm 0.043	0.030 \pm 0.026	0.014 \pm 0.013
Z_4^{-4}	0.038 \pm 0.033	0.023 \pm 0.020	0.012 \pm 0.011	0.005 \pm 0.004
Z_4^{-2}	0.027 \pm 0.023	0.017 \pm 0.015	0.009 \pm 0.008	0.003 \pm 0.003
Z_4^0	0.128 \pm 0.096	0.064 \pm 0.049	0.028 \pm 0.022	0.010 \pm 0.008
Z_4^2	0.048 \pm 0.039	0.026 \pm 0.023	0.013 \pm 0.013	0.005 \pm 0.005
Z_4^4	0.043 \pm 0.038	0.025 \pm 0.022	0.013 \pm 0.012	0.005 \pm 0.005
Z_5^{-5}	0.025 \pm 0.022	0.011 \pm 0.010	0.004 \pm 0.003	0.001 \pm 0.001
Z_5^{-3}	0.024 \pm 0.021	0.010 \pm 0.009	0.003 \pm 0.003	0.001 \pm 0.001
Z_5^{-1}	0.028 \pm 0.024	0.012 \pm 0.011	0.004 \pm 0.004	0.001 \pm 0.001
Z_5^1	0.020 \pm 0.018	0.009 \pm 0.008	0.003 \pm 0.003	0.001 \pm 0.001
Z_5^3	0.018 \pm 0.016	0.008 \pm 0.007	0.003 \pm 0.002	0.001 \pm 0.001
Z_5^5	0.023 \pm 0.021	0.010 \pm 0.009	0.003 \pm 0.003	0.001 \pm 0.001
Z_6^{-6}	0.019 \pm 0.018	0.007 \pm 0.006	0.002 \pm 0.002	0.000 \pm 0.000
Z_6^{-4}	0.014 \pm 0.014	0.005 \pm 0.005	0.001 \pm 0.001	0.000 \pm 0.000
Z_6^{-2}	0.012 \pm 0.011	0.004 \pm 0.004	0.001 \pm 0.001	0.000 \pm 0.000
Z_6^0	0.024 \pm 0.020	0.008 \pm 0.007	0.002 \pm 0.002	0.000 \pm 0.000
Z_6^2	0.016 \pm 0.016	0.006 \pm 0.006	0.002 \pm 0.002	0.000 \pm 0.000
Z_6^4	0.017 \pm 0.016	0.006 \pm 0.006	0.002 \pm 0.002	0.000 \pm 0.000
Z_6^6	0.020 \pm 0.018	0.007 \pm 0.006	0.002 \pm 0.002	0.000 \pm 0.000

For 3rd through 5th-order aberrations, $n = 2205$ for 6.0 mm and $n = 2560$ for 5.0, 4.0, and 3.0 mm; for 6th-order aberrations $n = 1871$ for 6.0 mm and $n = 2008$ for 5.0, 4.0, and 3.0 mm

double the means (normalized value 2.0). Figure 8 shows the same analysis for normalized RMS values for combined modes. As in Figures 6 and 7, approximately 60% of the sample population had RMS values less than the means (normalized value 1.0). From 92% to 97% of the population had RMS values less than double the means. In summary, for each Zernike mode or RMS category listed in Tables 2 and 3, 60% of the population had values less than the means and 90% to 97% had values less than double the means.

Correlation with Age

A detailed analysis of wavefront trends with respect to variables such as age or refractive error is beyond the scope of this study; however, a limited analysis of HOAs and age is presented. Figure 9 shows the distribution of Z_4^0 values for a 5.0-mm pupil (right eyes and left eyes) plotted as a function of age. A 2nd-order regression line ($y = 0.000045x^2 - 0.002038x + 0.06408$; $R = 0.249$) provided a slightly better fit to the data than a linear regression; it indicated on average, a gradual increase in the Z_4^0 value for the age range shown. There was, however, wide variability within each age level, indicating that factors other than age have a larger affect on Z_4^0 . Zernike modes Z_3^{-1} , Z_3^1 , and Z_4^2

showed highly significant age correlations (right eye, 5.0-mm pupil) with Spearman rho (r) coefficients between 0.10 and -0.12 ($P < .01$; $n = 1234$). Mode Z_4^4 showed a significant correlation with age ($r = 0.06$, $P = .03$). All RMS categories in Table 3 (right eye, 5.0 mm pupil) also showed highly significant correlations with age ($r < 0.20$, $P < .01$).

DISCUSSION

Although aberrometry is a valuable tool for diagnosing eyes with abnormal optics, diagnosis requires comparison to reference norms. A need for a recognized set of reference norms prompted this study. We collected normal-eye data from multiple sources and compiled a large heterogeneous (although normal) sample population of 2560 eyes. Two recent studies^{23,24} measured normal populations using a different technique, the Nidek OPD Scan, and reported results comparable to ours. Another study²⁵ using clinical Shack-Hartman aberrometry showed some results that were approximately 30% smaller than ours. We limited the assessment to data collected by Shack-Hartmann aberrometry for pupil diameters of at least 5.0 mm.

Figures 1 and 2 show good agreement between the different data sets for mean signed and absolute Zernike

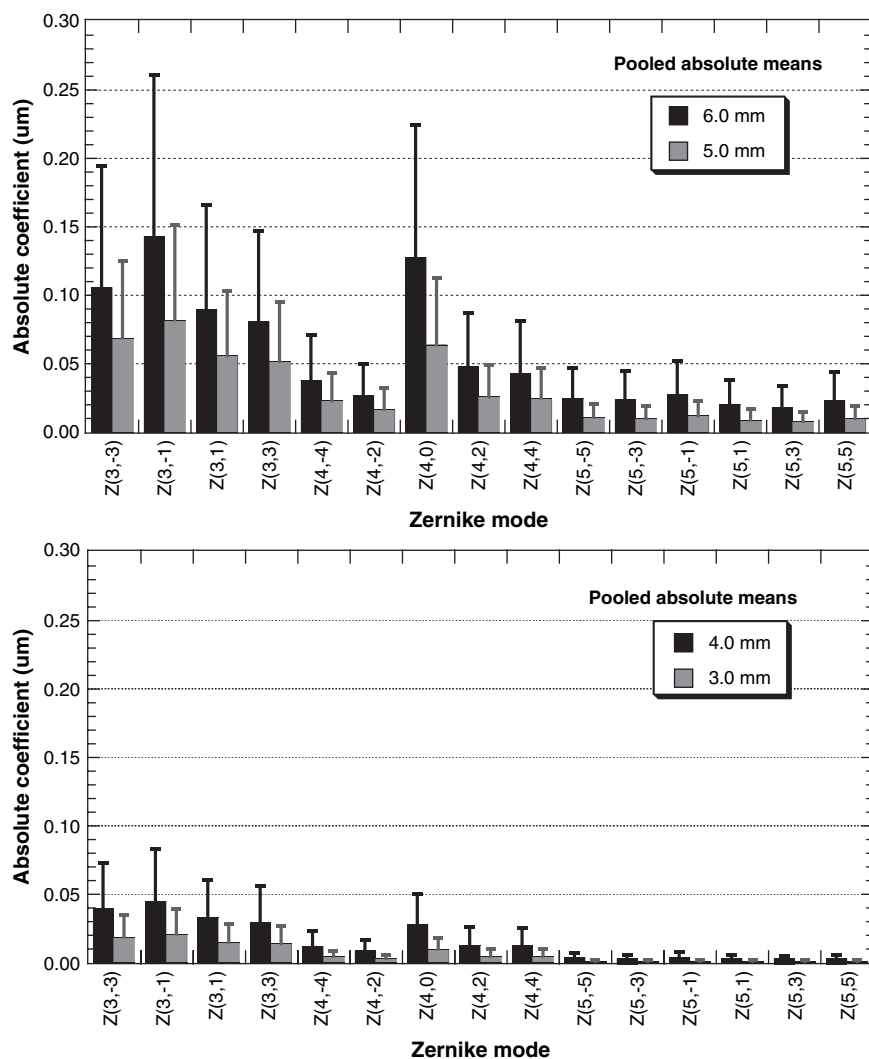


Figure 3. Mean absolute Zernike coefficients pooled for the entire data pool (both eyes) for pupil diameters of 6.0 and 5.0 mm (top) and 4.0 and 3.0 mm (bottom). Error bars indicate standard deviations.

coefficients for most Zernike modes. The consistency between data samples is remarkable considering the data came from 7 sites. The 3 largest data sets (Navy1, Navy2, and Baylor) used the same instrument, the WaveScan, and they showed very close agreement across all modes. The mean Zernike coefficients for Z_4^0 (spherical aberration) showed a greater spread between data sets, with the mean values clustering into 2 groups. At this point, we can only speculate whether age or ethnicity may have been a factor in the larger Z_4^0 mean values for the Tokyo data. We did not find other factors common to or distinct between the 2 clusters of Z_4^0 mean values that would explain the segregation into those clusters.

Tables 2 and 3 show means and standard deviations that may be useful for diagnosing wavefront measurements

in eyes with abnormal optics. For example, measurements that exceed the mean plus 2 standard deviations would be suspicious because 96% of the presumably normal population had lower absolute coefficients or RMS values. By incorporating statistics such as this, future aberrometers could simplify data interpretation by listing not only the Zernike coefficient but also the probability of finding that value in a normal population. Until then, clinicians can refer to Tables 2 and 3 when interpreting aberrometer data. The analyses in Figures 6 to 8 show that at least 90% of the sample had values less than or equal to double the means. This suggests a simplified rule-of-thumb for diagnosing aberrometry: Measurements greater than double the means listed in Tables 2 and 3 are found in less than 10% of the normal population and would therefore raise

Table 3. Mean RMS values \pm 1 standard deviation (μm) for polar and combined Zernike modes, Zernike orders, and total HDAs (orders 3 to 5) for 4 pupil diameters. Pooled from all right eye and left eye data.

Root Mean Square	Pupil Diameter (mm)			
	6.0	5.0	4.0	3.0
Polar modes				
Z ₃₁	0.185 \pm 0.118	0.109 \pm 0.069	0.061 \pm 0.039	0.029 \pm 0.018
Z ₃₃	0.147 \pm 0.091	0.095 \pm 0.058	0.055 \pm 0.035	0.026 \pm 0.017
Z ₄₀	0.128 \pm 0.096	0.064 \pm 0.049	0.028 \pm 0.022	0.010 \pm 0.008
Z ₄₂	0.060 \pm 0.039	0.034 \pm 0.023	0.018 \pm 0.013	0.007 \pm 0.005
Z ₄₄	0.063 \pm 0.042	0.038 \pm 0.025	0.020 \pm 0.013	0.008 \pm 0.005
Z ₅₁	0.039 \pm 0.025	0.017 \pm 0.011	0.006 \pm 0.004	0.001 \pm 0.001
Z ₅₃	0.033 \pm 0.022	0.014 \pm 0.010	0.005 \pm 0.003	0.001 \pm 0.001
Z ₅₅	0.037 \pm 0.025	0.016 \pm 0.011	0.005 \pm 0.004	0.001 \pm 0.001
Z ₆₀	0.024 \pm 0.020	0.008 \pm 0.007	0.002 \pm 0.002	0.000 \pm 0.000
Z ₆₂	0.023 \pm 0.017	0.008 \pm 0.006	0.002 \pm 0.002	0.000 \pm 0.000
Z ₆₄	0.025 \pm 0.018	0.009 \pm 0.007	0.002 \pm 0.002	0.000 \pm 0.000
Z ₆₆	0.030 \pm 0.022	0.010 \pm 0.008	0.003 \pm 0.002	0.000 \pm 0.000
Combined modes				
Coma-like (Z _{3\pm1} + Z _{5\pm1})	0.192 \pm 0.115	0.112 \pm 0.068	0.062 \pm 0.039	0.029 \pm 0.018
Spherical aberration-like (Z _{40} + Z _{60})	0.133 \pm 0.094	0.065 \pm 0.048	0.029 \pm 0.021	0.010 \pm 0.008
Zernike order				
3	0.251 \pm 0.123	0.153 \pm 0.075	0.087 \pm 0.043	0.041 \pm 0.021
4	0.169 \pm 0.090	0.090 \pm 0.046	0.043 \pm 0.022	0.016 \pm 0.008
5	0.067 \pm 0.034	0.030 \pm 0.016	0.010 \pm 0.005	0.002 \pm 0.001
6	0.057 \pm 0.030	0.020 \pm 0.011	0.005 \pm 0.003	0.001 \pm 0.001
Total higher order (orders 3–6)	0.327 \pm 0.130	0.186 \pm 0.078	0.100 \pm 0.044	0.045 \pm 0.021

For 3rd through 5th-order aberrations, n = 2205 for 6.0 mm and n = 2560 for 5.0, 4.0, and 3.0 mm; for 6th-order aberrations, n = 1871 for 6.0 mm and n = 2008 for 5.0, 4.0, and 3.0 mm

suspicion. For example, we would be suspicious of an eye that had a total higher-order RMS value for a 6.0-mm pupil greater than 0.66 μm .

This database contains a wealth of information that will allow further investigation of normal-eye aberrations, such as how HOAs vary with respect to refractive error,

age, or sex. Our analysis showed that 3rd-order Zernike modes Z_{3 $^{-1}$} , and Z_{3 1} ; 4th-order modes Z_{4 0} , Z_{4 2} , and Z_{4 4} ; and all RMS categories in Table 3 were significantly correlated with age. However, correlation coefficients were small and HOA values spanned a broad range at all ages. This indicates that although age is significant, factors other than

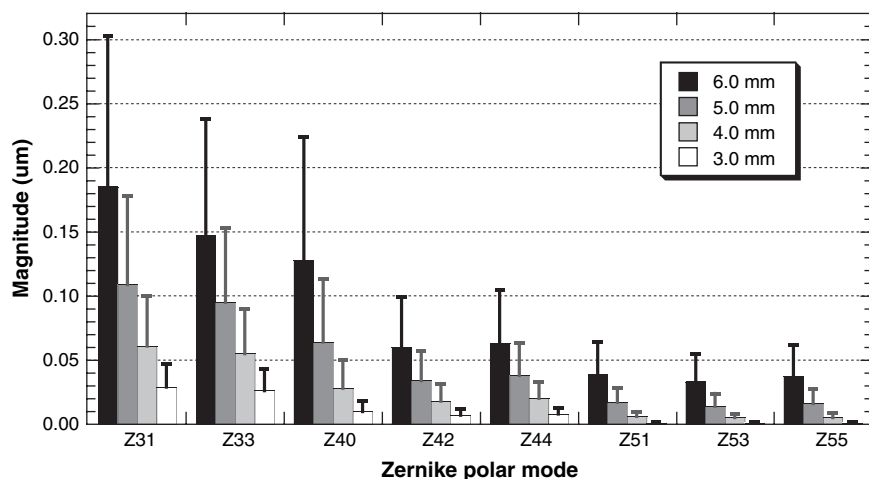


Figure 4. Mean polar Zernike magnitudes pooled from the entire data pool (both eyes) for four pupil diameters. Error bars show standard deviations.

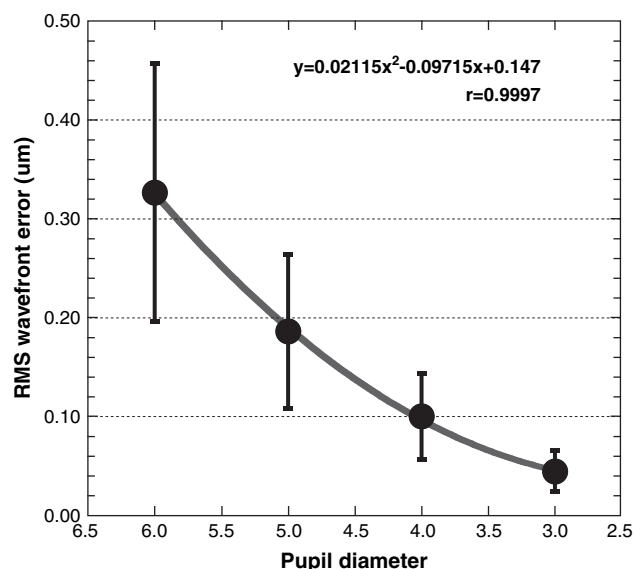


Figure 5. Mean total higher-order RMS wavefront error for the entire data pool (both eyes) as a function of pupil diameter. Error bars indicate 1 standard deviation. Linear regression equation with correlation coefficient is shown.

age play a greater role in determining the HOAs of an individual. Earlier studies using smaller sample sizes concluded that certain HOAs change with age,^{9,10,26-32} but they also noted large variance at all ages. Research indicates

that on average, a process of emmetropization causes a decline in aberrations up to young adulthood,^{9,30} when corneal and internal optical aberrations reach an optimum balance. Beyond middle age, lenticular changes gradually degrade the corneal-internal balance, leading to an increase in HOAs in older eyes.³¹ Lenticular Z_4^0 appears to be particularly important in this trend.³²

The following points summarize the HOAs in normal, healthy adult eyes:

- The most prominent Zernike modes and their mean absolute values for a 6.0-mm pupil are Z_3^{-1} (0.14 μm), Z_4^0 (0.13 μm), and Z_3^{-3} (0.11 μm).
- On average, the coefficients for Z_3^{-3} and Z_3^{-1} tend to be negative, but Z_4^0 is positive.
- All 3rd-order aberrations (Z_3^{-3} , Z_3^{-1} , Z_3^1 , Z_3^3) have significant non-zero mean absolute coefficients.
- The expected mean total higher-order RMS value (orders 3 to 6) is 0.33 μm for a 6.0-mm pupil. At least 90% of normal eyes should have absolute coefficients or RMS values less than double the mean values listed in Tables 2 and 3.

In conclusion, we found a good consensus among several laboratories describing the mean HOAs expected in normal adult eyes. This allowed us to compile a reference table with expected normal mean values and a suggested reference range for absolute Zernike coefficients and RMS

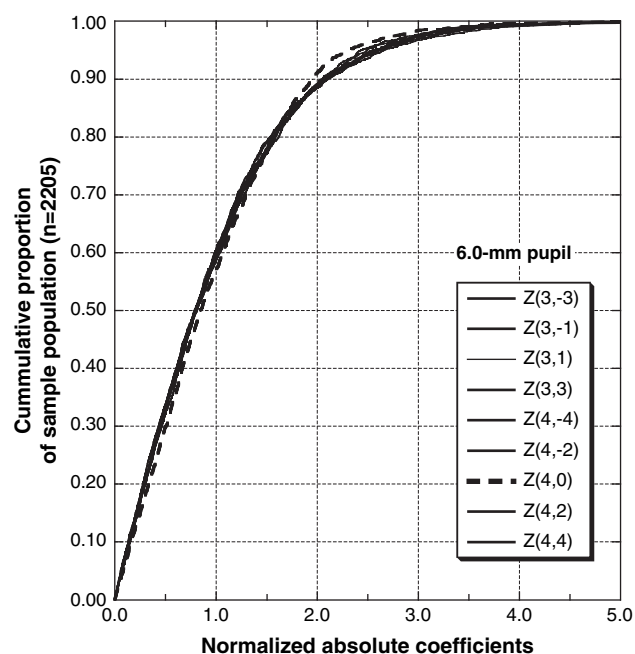


Figure 6. Proportion of the sample population with normalized absolute Zernike coefficients less than or equal to x-axis values for all 3rd- and 4th-order modes in all eyes.

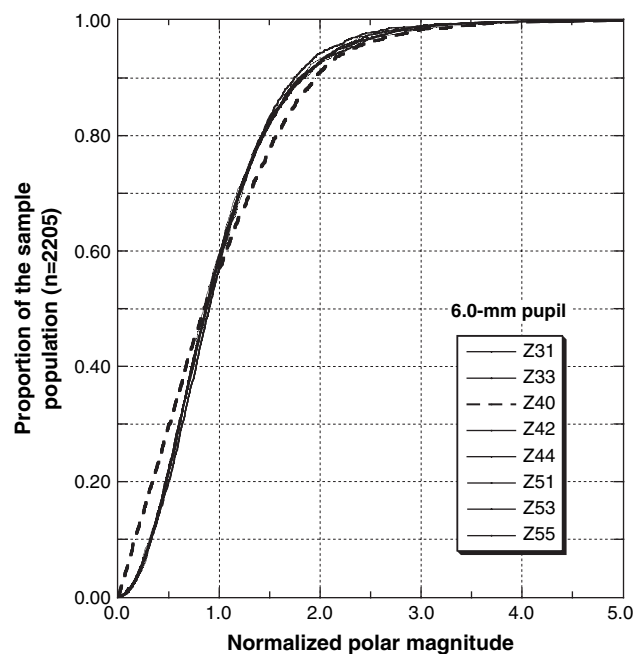


Figure 7. Proportion of the sample population with normalized polar Zernike magnitudes less than or equal to x-axis values for all 3rd- and 4th-order modes in all eyes.

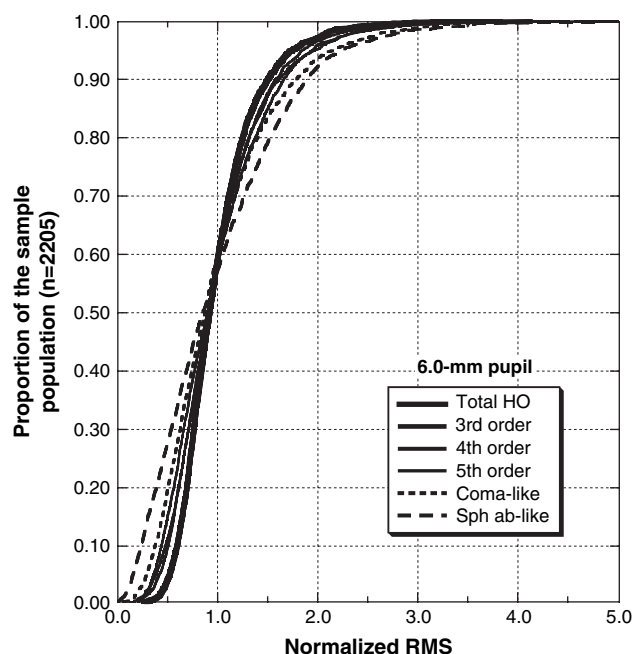


Figure 8. Proportion of the sample population with normalized RMS values less than or equal to x-axis values for the listed combined modes in all eyes.

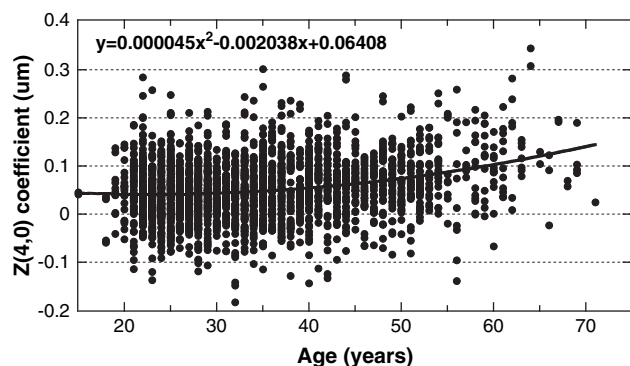


Figure 9. The Z_4^0 coefficient values plotted as a function of age for a 5.0-mm pupil (both eyes) with 2nd-order regression line ($R = 0.249$; $R^2 = 0.062$; $P < .01$; $n = 2552$).

wavefront errors. Future studies will provide more details about the role of age, refractive error, and other variables on HOAs in normal eyes.

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