INTRODUCTION TO ABERROMETRY & VISUAL OPTICS REVIEW

AUTHOR

Thomas Salmon: Northeastern State University, USA

PEER REVIEWER

Scott Steinman: Southern California College of Optometry, USA

THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Aberrometry
- Visual optics
- Basics of aberrometry
- Higher order aberrations
- Accuracy of aberrometers
- Aberration balancing in the human eye
- Adaptive optics correction of the eye
- Relationship between RMS, Zernike coefficients and vision

INTRODUCTION TO ABERROMETRY

"Next to life itself, God's most precious gift is the gift of sight." President Frank Devlyn.

As optometric physicians, one of our missions in life is to protect, restore and enhance the vision of our patients. What are some of the causes of poor vision?

- Eye diseases such as glaucoma or cataracts
- Systemic diseases such as a brain tumor that impinges on the visual pathways
- Eye injuries, such as blunt trauma to the eye during a basketball game
- Developmental anomalies such as amblyopia
- Refractive errors

INTRODUCTION TO ABERROMETRY (CONT.)

By far, the most common cause of poor vision is an uncorrected refractive error, so one of the most important things we do is to evaluate the eye's optical quality. Knowledge of optics makes optometric physicians the best-qualified professionals to care for the visual needs of patients. Let's discuss one of the most exciting recent developments in the field of visual optics—aberrometry.

Q. What is aberrometry?

A. Aberrometry is also known as wavefront sensing. It is a technique used to measure refractive errors in much greater detail than is possible with traditional clinical refraction methods such as subjective refraction using a phoropter or autorefraction.

Wavefront is defined as the surface associated with a propagating wave that is determined by associating all points in the wave that have the same phase.

Aberrometry takes a different approach to measuring refractive errors. It measures the shape of a wavefront of light that has passed through the optical elements of the eye. By analyzing the wavefront's shape, we can determine the amount and kinds of refractive errors present in the eye, including:

- Spherical defocus errors (myopia, hyperopia)
- Astigmatic errors
- Higher-order aberrations (coma, spherical aberrations and others)

VISUAL OPTICS REVIEW

SIMILARITIES BETWEEN THE EYE AND A CAMERA

The human eye is often likened to a camera. Both are optical instruments that have been designed to form images. Other similarities are summarized in Table 1- 1.

SCHEMATIC EYES

The camera illustration can help us understand the eye, and schematic eyes have also been useful for this purpose. Examples include:

- Gullstrand's No. 1 schematic eye. Two-surface cornea, four-surface lens, spherical, rotationally symmetric surfaces
- Gullstand-Emsley reduced eye. One-surface cornea, two-surface lens, spherical, rotationally symmetric surfaces (see Fig. 1-1)
- Indiana Eye. One-surface aspheric cornea with a pupil. See the article at the following web site: (http://research.opt.indiana.edu/Library/INEye/IndianaEye.html) or in Thibos LN, Ye M, Zhang X, BradleyA. Spherical Aberration of the Reduced Schematic Eye with Elliptical Refracting Surface. Optom Vis Sci 1997; 74:458-556

Table 1-1: *Similarities between the eye and a camera*

EYE	CAMERA	FUNCTION
Cornea + lens	Lens elements	Focus light, form image
Retina	Film or CCD chip (digital camera)	Receive image, convert photons to an electrical signal
Pupil	Aperture	Control image brightness, depth of focus, diffraction, aberrations
RPE layer	Blackened interior	Reduce internal light scatter
Accommodation	Auto-focus mechanism	Focus for different distances

VISUAL OPTICS REVIEW (CONT.)

Q. What is the definition of the entrance pupil?

A. It is the image of the real pupil formed by the cornea. That is, if the anatomic pupil or iris is the object, after refraction by the cornea, the entrance pupil is its image. When we look at a person's eye and see the pupil or iris, we are not seeing the real pupil but an image of the pupil, that is, the entrance pupil. The entrance pupil is particularly important in aberrometry because it is the normal reference plane for measuring aberrations of the eye.

The Complete Ophthalmic Analysis System (COAS) aberrometer allows you to specify the aberrations in the spectacle or corneal plane, but the basic measurement is normally made at the entrance pupil plane.

AXES OF THE EYE

In visual optics you learned about several theoretical axes of the eye and important angles between those axes.

For the purposes of aberrometry, the most important axis of the eye is the line of sight.

The line of sight is defined as the line segment connecting the fixation point and the center of the entrance pupil. If a ray of light enters the eye on the line of sight, it will continue inside the eye from the exit pupil to the fovea. (Fig. 1-1) The line of sight is important in aberrometry, because measurements of the eye's aberrations should be centered on the line of sight.

Chapter 10 discusses neural considerations and the effective "grain" of the retina, as well as the Stiles-Crawford Effect. We will study these in more detail later in the coursework when we study spatial vision.

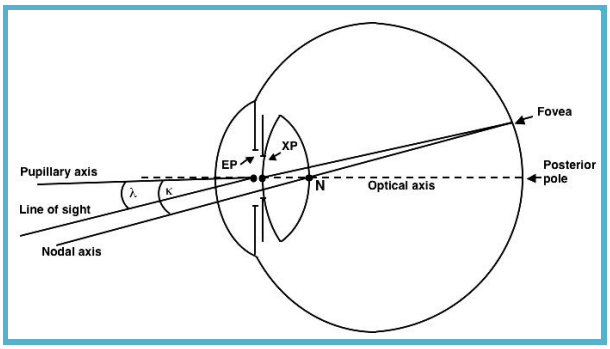


Figure 1-1: *Figure based on the Gullstrand-Emsley reduced eye showing some of the important axes and angles, as well as the location of the entrance and exit pupils*

XP – Exit pupil
EP – Entrance pupil
N – Nodal point

With regards to the methods for reporting optical aberrations of eyes, ANSI (American National Standard Institute) 2004 summarizes many of the basic principles of aberrometry and standardizes the systems of measuring and recording aberrations.

BASICS OF ABERROMETRY

- What are higher-order aberrations (HOAs)?
  - Refractive errors
- What are aberrometers?
  - Super auto-refractors
- What are Zernike polynomials?
  - A way to record refractive errors
- Who needs aberrometry?
  - Patients with poor vision due to higher-order aberrations

BASICS OF ABERROMETRY (CONT.)

WHAT ARE HIGHER-ORDER ABERRATIONS?	• Aberrations = refractive errors • Refractive errors include myopia, hyperopia, astigmatism and others • Lower-order refractive errors (aberrations): sphere, astigmatism • Higher-order refractive errors (aberrations): the others • Aberrometers measure monochromatic aberrations • Chromatic aberration is a different topic • Seidel aberrations are for man-made optical systems, not the eye
PUPIL SIZE IS CRITICAL	• Aberrations are most problematic for large pupil sizes • The greatest benefit from correcting HOAs is for large pupil sizes • One way to reduce problematic aberrations: reduce pupil size • Supernormal vision = vision with perfect (aberration-free) optics • Best visual acuity (BVA) is 20/8 or 6/2.4!
WHAT ARE ABERROMETERS?	• Also called wavefront sensors • Like super autorefractors. They measure sphere, cylinder and HOAs
WHAT DO ABERROMETERS MEASURE?	• Distortions in a wavefront of light that has passed through the eye's optics • Aberrations (refractive errors) distort optical wavefronts passing through the eye • Measure the shape of the wavefront to determine the aberrations in the eye • Shack-Hartmann aberrometers (the most popular type) measure the shape of a wavefront emitted from the eye after reflection by the retina
HOW DO YOU RECORD THE ABERRATIONS?	• Aberrometers measure wavefronts • Wavefronts are distorted by aberrations in the eye • Most eyes have a mix of multiple aberrations that cause irregular, distorted wavefronts. (See Fig 1-2)

Q. How can you diagnose the specific aberrations in the eye that caused those distortions?
A. Analyze the wavefront using Zernike polynomials.

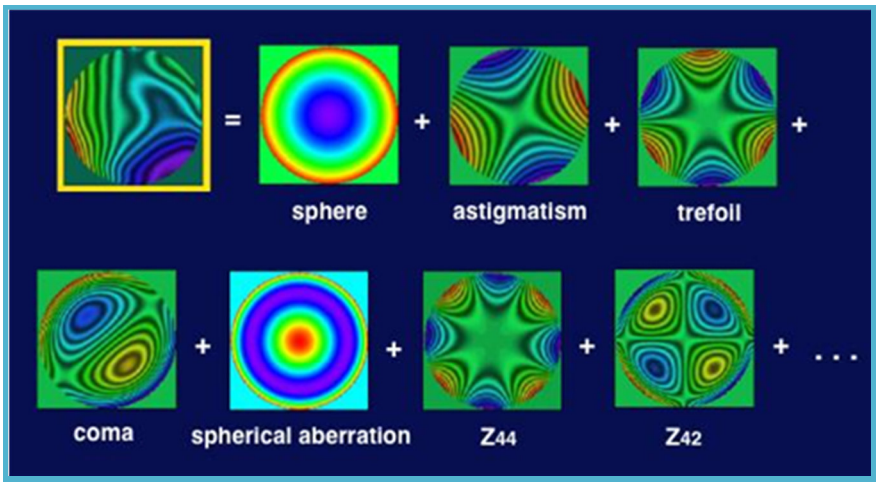


Figure 1-2: *The upper-left wavefront contains these aberrations*

- Zernike polynomials - the modern standard for reporting aberrations of the human eye (ANSI Z-80.28-2004)
- A mathematical system - arranges specific aberrations **(Zernike modes)**, into a hierarchy (see Fig 1-3).

BASICS OF ABERROMETRY (CONT.)

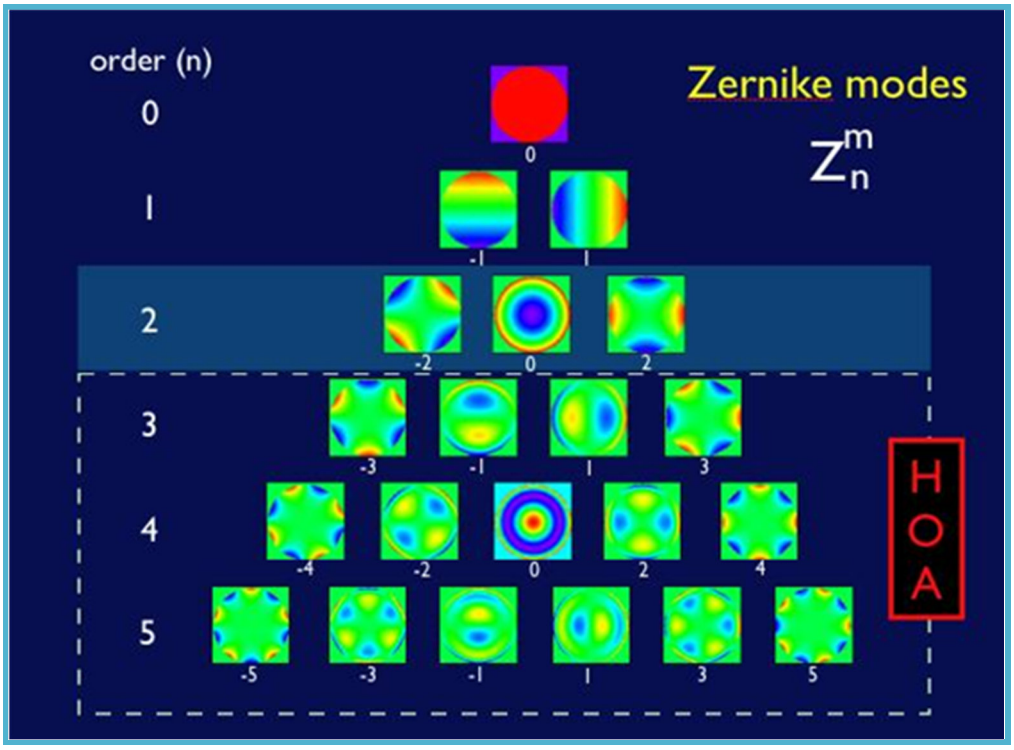


Figure 1-3: *Zernike modes arranged in a pyramid. Each mode is one aberration*

Periodic table of Zernike modes - a pyramid as show in Figure 1.3
Organized into Zernike orders (the rows). Only first 5 orders are shown in Figure 1.3
Zernike modes in each row are numbered.
Specific modes are identified by a subscript (n) and superscript (m). Z_n^m
Where n = order number; m = mode number
Second-order modes include sphere Z_2^0 and astigmatism Z_2^2 and Z_2^{-2}.
Third-order modes and above are known as higher-order aberrations (HOAs).

BASICS OF ABERROMETRY (CONT.)

Figure 1-4 shows an example of one eye's wavefront with its conventional and Zernike prescription (Rx).

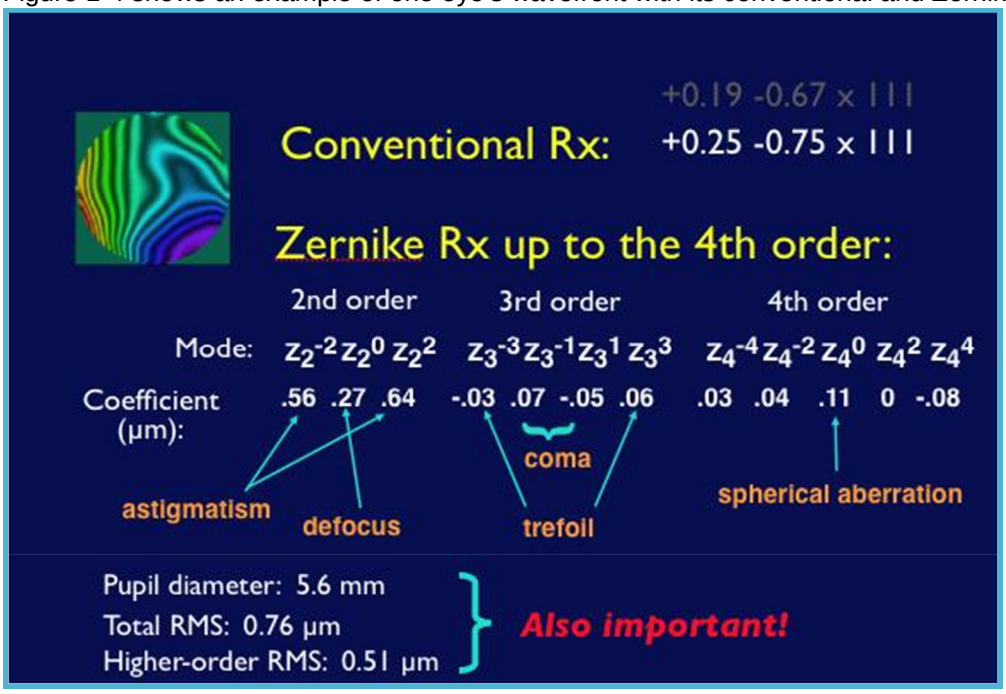


Figure 1-4: *Wavefront and data describing one eye's refractive errors*

Pupil size is a critical part of the Zernike data. The Zernike coefficients apply only for one pupil size. They will change if pupil size changes.

The unit for Zernike coefficients is the micrometer (µm).

Total Root Mean Square (RMS) = overall magnitude of all the eye's refractive errors (sphere, cylinder + HOAs).

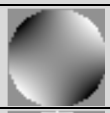
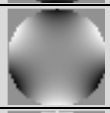
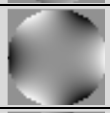
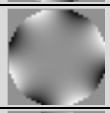
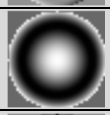
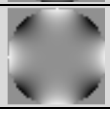
Higher-order RMS = magnitude of all the eye's HOAs together.

Case example

- 35-year-old female, came to the optometry clinic for a comprehensive eye exam
- Had radial keratotomy (RK) OU years before
- Complained of shadows/double vision/glare, eye strain, headaches, difficulty reading, especially at night, and during night driving
- Aberrometry revealed larger-than-normal HOAs (uncorrectable with spectacles) secondary to RK
- Prescribed α-2 adrenergic agonist (Brimonidine) drops to reduce pupil size
- Patient still using 1 year later. Vision improved, no glare, no headaches

BASICS OF ABERROMETRY (CONT.)

Table 1-2:*Zernike polynomials in the second through fourth orders*

ORDER	ZERNIKE MODE	NAME	EQUATION (POLAR)	TOPO MAP
2	Z_2^{-2}	Oblique astigmatism	$\sqrt{6}\rho^2\sin 2\theta$	
2	Z_2^{0}	Spherical defocus	$\sqrt{3}(2\rho^2-1)$	
2	Z_2^{2}	ATR/WTR* astigmatism	$\sqrt{6}\rho^2\cos 2\theta$	
3	Z_3^{-3}	Oblique trefoil	$\sqrt{8}\rho^3\sin 3\theta$	
3	Z_3^{-1}	Vertical coma	$\sqrt{8}(3\rho^3-2\rho)\sin\theta$	
3	Z_3^{1}	Horizontal coma	$\sqrt{8}(3\rho^3-2\rho)\cos\theta$	
3	Z_3^{3}	Horizontal trefoil	$\sqrt{8}\rho^3\cos 3\theta$	
4	Z_4^{-4}	Oblique quadrafoil	$\sqrt{10}\rho^4\sin 4\theta$	
4	Z_4^{-2}	Oblique 2nd order astigmatism	$\sqrt{10}(4\rho^4-3\rho^2)\sin 2\theta$	
4	Z_4^{0}	Spherical aberration	$\sqrt{5}(6\rho^4-6\rho^2+1)$	
4	Z_4^{2}	ATR/WTR* 2nd order astigmatism	$\sqrt{10}(4\rho^4-3\rho^2)\cos 2\theta$	
4	Z_4^{4}	Quadrafoil	$\sqrt{10}\rho^4\cos 4\theta$	

ATR = against the rule (maximum positive wavefront error at 180 degrees)
WTR = with the rule (maximum positive wavefront error at 90 degrees)

BASICS OF ABERROMETRY (CONT.)

Table 1-3: *Mean absolute Zernike coefficients ± standard deviation (μm) for pooled data (OD and OS combined) for four pupil diameters. (From Professor Thomas Salmon's study, to be published in the Journal of Cataract and Refractive Surgery.)*

ZERNIKE TERM	6.0 MM	5.0 MM	4.0 MM	3.0 MM
Z_3^{-3}	0.106 ± 0.088	0.069 ± 0.056	0.040 ± 0.033	0.019 ± 0 .016
Z_3^{-1}	0.143 ± 0.118	0.082 ± 0.069	0.045 ± 0.038	0.021 ± 0.018
Z_3^{1}	0.090 ± 0.076	0.056 ± 0.047	0.033 ± 0.027	0.015 ± 0 .013
Z_3^{3}	0.081 ± 0.066	0.052 ± 0.043	0.030 ± 0.026	0.014 ± 0.013
Z_4^{-4}	0.038 ± 0.033	0.023 ± 0.020	0.012 ± 0.011	0.005 ± 0 .004
Z_4^{-2}	0.027 ± 0.023	0.017 ± 0.015	0.009 ± 0.008	0.003 ± 0.003
Z_4^{0}	0.128 ± 0.096	0.064 ± 0.049	0.028 ± 0.022	0.010 ± 0 .008
Z_4^{2}	0.048 ± 0.039	0.026 ± 0.023	0.013 ± 0.013	0.005 ± 0.005
Z_4^{4}	0.043 ± 0.038	0.025 ± 0.022	0.013 ± 0.012	0.005 ± 0 .005
Z_5^{-5}	0.025 ± 0.022	0.011 ± 0.010	0.004 ± 0.003	0.001 ± 0.001
Z_5^{-3}	0.024 ± 0.021	0.010 ± 0.009	0.003 ± 0.003	0.001 ± 0 .001
Z_5^{-1}	0.028 ± 0.024	0.012 ± 0.011	0.004 ± 0.004	0.001 ± 0.001
Z_5^{1}	0.020 ± 0.018	0.009 ± 0.008	0.003 ± 0.003	0.001 ± 0 .001
Z_5^{3}	0.018 ± 0.016	0.008 ± 0.007	0.003 ± 0.002	0.001 ± 0.001
Z_5^{5}	0.023 ± 0.021	0.010 ± 0.009	0.003 ± 0.003	0.001 ± 0 .001
Z_6^{-6}	0.019 ± 0.018	0.007 ± 0.006	0.002 ± 0.002	0.000 ± 0.000
Z_6^{-4}	0.014 ± 0.014	0.005 ± 0.005	0.001 ± 0.001	0.000 ± 0 .000
Z_6^{-2}	0.012 ± 0.011	0.004 ± 0.004	0.001 ± 0.001	0.000 ± 0.000
Z_6^{0}	0.024 ± 0.020	0.008 ± 0.007	0.002 ± 0.002	0.000 ± 0 .000
Z_6^{2}	0.016 ± 0.016	0.006 ± 0.006	0.002 ± 0.002	0.000 ± 0.000
Z_6^{4}	0.017 ± 0.016	0.006 ± 0.006	0.002 ± 0.002	0.000 ± 0 .000
Z_6^{6}	0.020 ± 0.018	0.007 ± 0.006	0.002 ± 0.002	0.000 ± 0.000

For 3rd through 5th order aberrations, n=2,205 for 6.0 mm and n=2,560 for 5.0, 4.0, 3.0 mm
For 6th order aberrations, n=1871 for 6.0 mm and n=2,008 for 5.0, 4.0, 3.0 mm

BASICS OF ABERROMETRY (CONT.)

Table 1-4: *Mean RMS values ± standard deviation (µm) for polar and combined Zernike modes, Zernike orders and total higher-order aberrations (Orders 3-5) for four pupil diameters. Pooled from all OD and OS data (from Professor Thomas Salmon's study, to be published in the Journal of Cataract and Refractive Surgery)*

RMS FOR	6.0 MM	5.0 MM	4.0 MM	3.0 MM
POLAR MODES				
Z31	0.185 ± 0.118	0.109 ± 0.069	0.061 ± 0.039	0.029 ± 0.018
Z33	0.147 ± 0.091	0.095 ± 0.058	0.055 ± 0.035	0.026 ± 0.017
Z40	0.128 ± 0.096	0.064 ± 0.049	0.028 ± 0.022	0.010 ± 0.008
Z42	0.060 ± 0.039	0.034 ± 0.023	0.018 ± 0.013	0.007 ± 0.005
Z44	0.063 ± 0.042	0.038 ± 0.025	0.020 ± 0.013	0.008 ± 0.005
Z51	0.039 ± 0.025	0.017 ± 0.011	0.006 ± 0.004	0.001 ± 0.001
Z53	0.033 ± 0.022	0.014 ± 0.010	0.005 ± 0.003	0.001 ± 0.001
Z55	0.037 ± 0.025	0.016 ± 0.011	0.005 ± 0.004	0.001 ± 0.001
Z60	0.024 ± 0.020	0.008 ± 0.007	0.002 ± 0.002	0.000 ± 0.000
Z62	0.023 ± 0.017	0.008 ± 0.006	0.002 ± 0.002	0.000 ± 0.000
Z64	0.025 ± 0.018	0.009 ± 0.007	0.002 ± 0.002	0.000 ± 0.000
Z66	0.030 ± 0.022	0.010 ± 0.008	0.003 ± 0.002	0.000 ± 0.000
COMBINED MODES				
Coma-like (Z31+Z51)	0.192 ± 0.115	0.112 ± 0.068	0.062 ± 0.039	0.029 ± 0 .018
Sphaberr-like (Z40+Z60)	0.133 ± 0.094	0.065 ± 0.048	0.029 ± 0.021	0.010 ± 0.008
ZERNIKE ORDERS				
3	0.251 ± 0.123	0.153 ± 0.075	0.087 ± 0.043	0.041 ± 0.021
4	0.169 ± 0.090	0.090 ± 0.046	0.043 ± 0.022	0.016 ± 0.008
5	0.067 ± 0.034	0.030 ± 0.016	0.010 ± 0.005	0.002 ± 0.001
6	0.057 ± 0.030	0.020 ± 0.011	0.005 ± 0.003	0.001 ± 0.001
Total HO (Orders 3-6)	**0.327 ± 0.130**	**0.186 ± 0.078**	**0.100 ± 0.044**	**0.045 ± 0.021**

For 3rd through 5th order aberrations, n=2,205 for 6.0 mm and n=2,560 for 5.0, 4.0, 3.0 mm
For 6th order aberrations, n=1871 for 6.0 mm and n=2,008 for 5.0, 4.0, 3.0 mm

HIGHER-ORDER ABERRATIONS (HOA)

Table 1-5: *Examples of data from a Visual Psychophysics and Neurophysiology (VPN) class. Row 1 shows the Zernike coefficients for an HOA elite eye.*

ENTITY	PUPIL	HO RMS	Z (3, −3)	Z (3, −1)	Z (3, 1)	Z (3, 3)	Z (4, 0)
Last year's best	6.0	0.13	−0.07	0.02	−0.09	0.01	0.00
Class 12 best	5.0	0.11	−0.02	0.00	0.04	0.07	0.02
Class mean	5.0	0.21	0.00	−0.01	0.00	−0.01	0.04
Class absolute mean	5.0	0.21	0.08	0.08	0.06	0.07	0.07
OCO absolute norms	5.0	0.19	0.07	0.08	0.06	0.05	0.06
LASIK eye (absolute)	6.0	0.34	0.09	0.02	0.09	0.02	0.27
LASIK ratios		1.03	0.81	0.14	1.00	0.25	2.07

How would you compute the mean value for each HOA for the class?

- Add up each subject's value
- Divide by the number of subjects
- For most aberrations, except spherical aberration Z(4,0), the mean is usually close to zero. Can you explain why? Note that this was true for the class also.
- Why would we like to know the mean of the absolute values?
- Note how the class mean compares with the Oklahoma College of Optometry (OCO) norms (Published in JCRS in Dec, 2006)

HIGHER-ORDER ABERRATIONS (HOA) (CONT.)

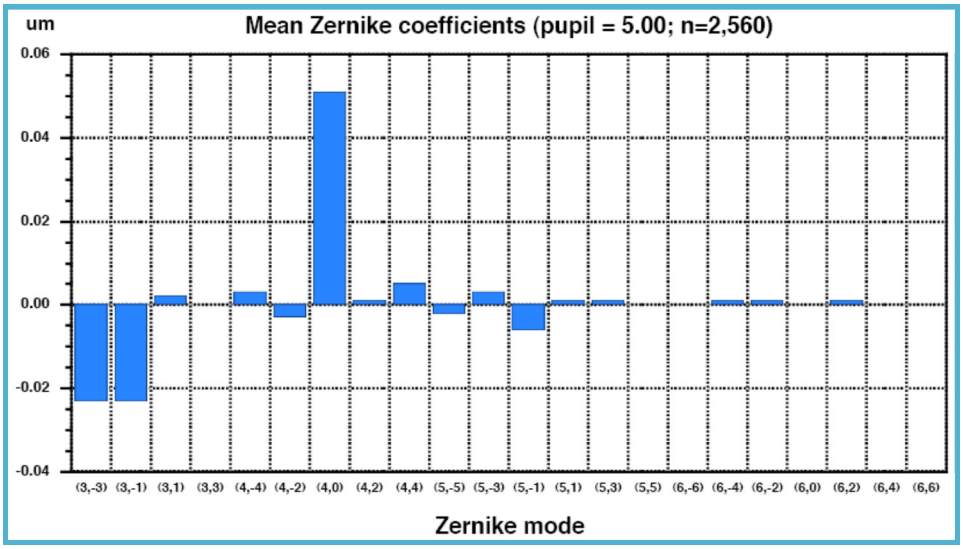


Table 1-5: *Zernike coefficients for 5mm pupil size*

Scaling Zernike coefficients to a different pupil diameter

Approximate formula to scale the value of a Zernike coefficient to a different pupil size:

$$\text{Coefficient2} = \frac{\text{pupil2}\wedge n}{\text{pupil1}\wedge n}(\text{coefficient1})$$

Where n = Zernike order for that coefficient.

Example problem

Assume value of Z_4^0 (spherical aberration) for a 6.0-mm diameter pupil is 0.13. Estimate the value of Z_4^0 for a 5.0-mm diameter pupil:

- Coefficient1 = 0.13 µm
- Pupil diameter1 = 6.0 mm
- Pupil diameter2 = 5.0 mm
- n = 4 (fourth order aberration)

$$\text{Coefficient2} = \frac{5\wedge 4}{6\wedge 4}(0.13) = (0.48)(0.13) = 0.06\ \mu\text{m}$$

Note that this formula applies to a single Zernike mode, not to RMS, which combines modes. To compute a scaled RMS value, you must:

- Scale each Zernike coefficient one by one
- Compute the RMS for the modes you want to combine

COMPUTING RMS

Given the coefficients for each Zernike mode, you can easily compute the RMS value for those modes combined. This allows you to quantify the overall magnitude of the aberrations (Zernike modes) combined. The formula for RMS is:

$$\text{RMS} = \sqrt{\sum\left[(C_n^m)^2 + (C_n^m)^2 + (C_n^m)^2 + K\right]}$$

HIGHER-ORDER ABERRATIONS (HOA) (CONT.)

Where, C_n^m refers to the Zernike coefficients of interest. You can compute the RMS wavefront error for any combination of Zernike modes, but it is used most often for the total HOAs or for the combined effect of all the modes in one order.

For example, using the Zernike coefficient values from Row 1 of Table 3-1 (the elite eye), compute the RMS for third-order aberration combined.

$$\text{RMS} = \sqrt{\sum[(-0.07)^2 + (0.02)^2 + (-0.09)^2 + (0.01)^2 + (0)^2]} = 0.12\ \mu\text{m}$$

ACCURACY OF ABERROMETERS

Early work, including Professor Thomas Salmon's research at Northeastern State University, tested the accuracy of Shack-Hartmann sensors for measuring optics of the human eye. With test lenses, his aberrometer was able to measure distortions as small as 0.02 µm, which is equivalent to about 0.008 diopter (D) of refractive error. This level of accuracy is difficult to attain with the human eye because of factors such as:

- Head and eye movements during the measurement.
- Fluctuations in accommodation and pupil size.
- Fluctuations in the tear layer.

In addition, it is difficult to validate such a precise instrument, since it far exceeds any other method for measuring refractive errors of eyes. He found, however, that there was very close agreement between subjective aberrometry (using a technique invented by Smirnov in the 1960s – Fig. 1-6) and Shack-Hartmann measurements of the same eyes (Fig. 1-7). His research showed that, on average, COAS measurements of sphere and cylinder agree well with subjective clinical refraction. Other recent research with model eyes has verified that Shack-Hartmann aberrometers provide accurate measurements of higher-order aberrations.

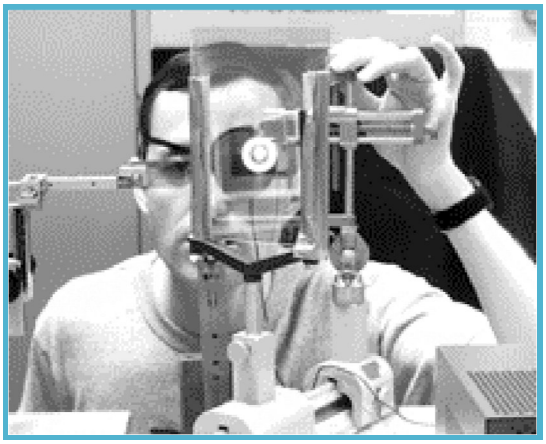


Table 1-6:*Measuring aberrations using a Smirnov-type device*

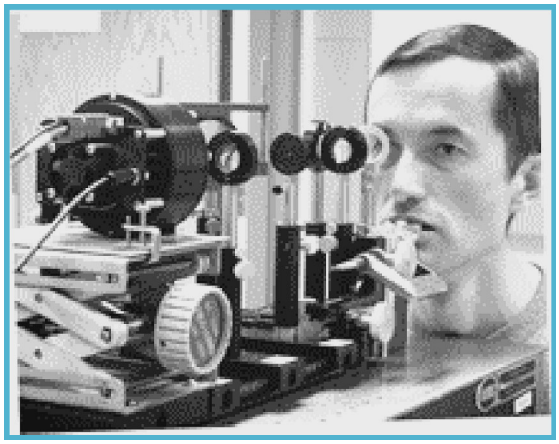


Table 1-7:*Using a Shack-Hartmann sensor*

ABERRATION BALANCING IN THE HUMAN EYE

Lens designers optimize man-made optical imaging systems by balancing positive aberrations of one element against negative aberrations in another. This happens to some extent with astigmatism. The cornea often has a with-the-rule astigmatism but the lens usually has a slight against-the-rule astigmatism. As a result, the total astigmatism of the eye is usually less than that of the cornea.

For years, scientists speculated about whether balancing occurs for the higher-order aberrations. Effective balancing between the cornea and lens varies from person to person, and in the same person, from mode to mode. Some people have a beneficial balance (lens helps neutralize the cornea), while some have an adverse balance (lens aberrations add to those of the cornea) for certain modes.

A study by Artal et al (2002) suggested that for many healthy, young adult eyes, internal higher-order aberrations tend to have the opposite sign of the corresponding corneal aberrations. In these cases, corneal aberrations will be balanced by internal optics and the effectiveness of the balance will depend on the relative magnitudes of the corneal and internal aberrations. With time and age-related lens changes, the effective balance in these eyes seems to break down, and as a result, whole-eye aberrations tend to increase with age (Fig. 1-8).

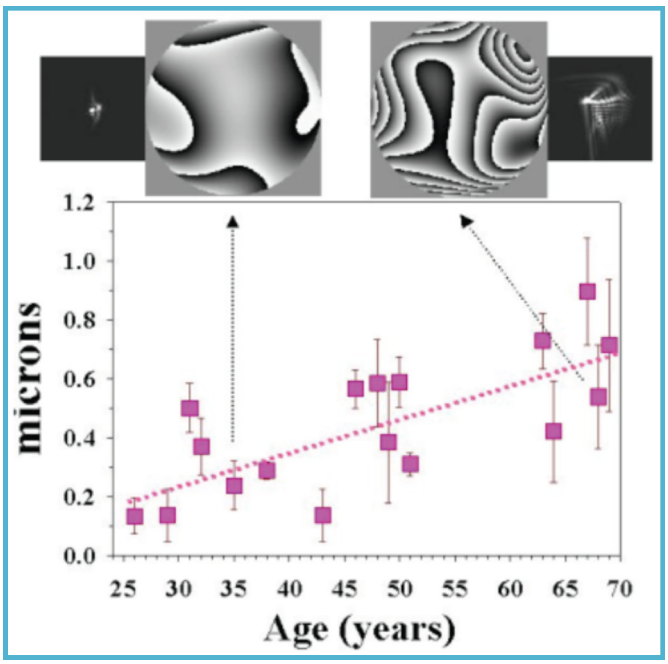


Table 1-8:*Changes in aberrations with age*

Total higher-order wavefront aberrations (RMS error) for 17 eyes, ranging in age from 25 to 70 years. Higher-order aberrations seem to increase with age, though there are individual variations. Arrows indicate wave aberration maps and point spread functions corresponding to two data points, for a younger and older eye. (From: Artal P, Guirao A, Berrio E, Williams DR. J Vision, 2001;1: 1-8. Copied with permission)

ADAPTIVE OPTICS CORRECTION OF THE EYE

Wavefront sensors were originally developed for the military and astronomy to measure and then compensate for atmospheric aberrations. Today, most of the world's largest telescopes have Shack-Hartmann wavefront sensors to measure the aberrations, and a deformable mirror to correct the aberrations. Adaptive optics (AO) refers to systems that measure and correct for aberrations, especially higher-order aberrations. AO systems, originally used in astronomy, have also been applied to the human eye to:

1. Correct vision
2. Improve fundus photography

ADAPTIVE OPTICS CORRECTION OF THE EYE (CONT.)

VISUAL BENEFITS OF CORRECTING ABERRATIONS

Researchers at the University of Rochester Center for Visual Science corrected ocular monochromatic aberrations with a deformable mirror and measured how much vision improved. They also studied the benefit of correcting chromatic aberration and correcting both monochromatic and chromatic aberrations. Correction of chromatic aberration alone provided slightly better vision that the best spectacle prescription. Correction of monochromatic aberrations alone provided even better vision, and the best improvement was seen when both chromatic and monochromatic higher-order aberrations were corrected (Figure 1-9).

ADAPTIVE OPTICS FUNDUS PHOTOGRAPHY

Visual correction is not the only clinical benefit of adaptive optics. Correction for the eye's aberrations also allows much clearer images of the retina. Researchers at the University of Rochester Center designed an adaptive optics ophthalmoscope that provided never-before-seen views of the microstructure of the living retina (Figure 1-10), including photos of individual macular cones. This allowed Drs. Austin Roorda and David Williams to study the arrangement of S, M and L cones, which are the three photoreceptor types that provide basic sensory input for color vision.

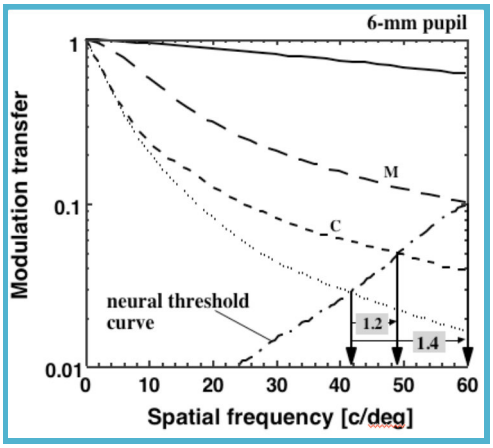


Table 1-9:*Theoretical modulation transfers (MTFs) after correction of defocus and astigmatism only (lower curve), additional correction of chromatic aberration only (curve C), correction of defocus, astigmatism and monochromatic aberrations (curve M) and correction of all aberrations (top curve). Visual acuity improves by a factor of 1.2 when chromatic aberrations are corrected and by a factor of 1.4 when monochromatic aberrations are corrected. (From: Yoon GY and Williams DR. J. Opt. Soc. Am. A, 2002;19: 266-275. Copied with permission.)*

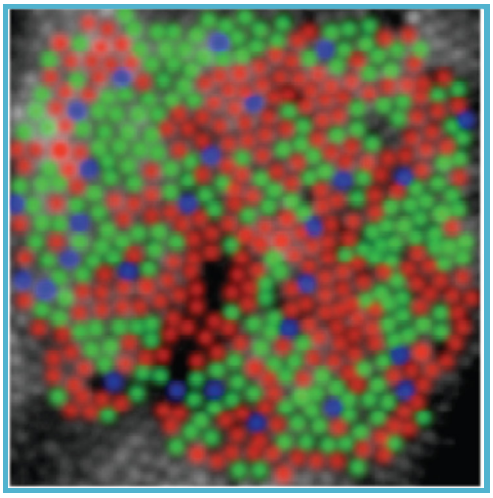


Table 1-10:*High-resolution fundus photo showing individual cones in the macula*

False color is added to identify the S (blue), M (green) and L (red) cones. Obtained using an adaptive optics fundus camera. Courtesy of Dr. Austi**n Roorda, University of Houston**

RELATIONSHIP BETWEEN RMS, ZERNIKE COEFFICIENTS & VISION

Studies have shown that, for eyes with large aberrations, there is a good correlation between total HO RMS and vision. However for eyes with smaller aberrations, there is a poor correlation between HO RMS and VA. (Applegate, Ballentine, Gross, Sarver & Sarver, 2003a).

The relationship between optics and vision is further muddled because, as Applegate has shown, not all aberrations are equal. (Applegate, Sarver & Khemsara, 2002). Some modes degrade VA worse than others, even with the same amount of mode-RMS error. When considering individual modes in isolation, those with a smaller superscript (m of "Z_n^m), within each Zernike order (that is, modes near the middle of the pyramid), have a more drastic adverse effect on VA. For example, 0.2 µm of Z_4^0 is worse than 0.2 µm of Z_4^{-2} or Z_4^4.

Applegate et al (2003b) studied the effect on vision of pairs of Zernike modes and found that the interaction between modes is complex. For some pairs of modes, the aberrations in one mode can help neutralize the aberrations in another mode. For example, 0.25 µm RMS of defocus alone Z_2^0 can be worse than an RMS of 0.25 µm for Z_2^0 and Z_4^0 combined. On the other hand, some modes exacerbate the adverse affect on vision. For example, 0.25 µm of RMS for Z_4^0 plus Z_4^{-2} is worse than 0.25 µm RMS of Z_4^0 alone (Applegate et al., 2003a).

The conclusion is that RMS is a poor predictor of vision when aberrations are relatively small. This would be the case in a well-corrected normal eye, or an eye that had successful wavefront-guided refractive surgery. Thibos and others therefore attempted to find some metric, mathematically derived formula from Zernike coefficients, which would do a good job of predicting VA. He tested 33 metrics, and came up with several that worked well. They worked so well, that he speculated that they might do better than subjective refraction (our gold standard) in determining the spectacle refraction that would give the best VA (Thibos et al, 2004).

EXAMPLES OF RECENT ABERRATION RESEARCH

- Aberrometry was used to compare how two different artificial tears behave on the eye.
- Aberrometry was used to study changes in optics of the eye that accompanied changes in blood glucose levels for non-diabetics and a diabetic subject.
- Aberrometry was used to compare optical quality of two aspheric contact lenses that claim to correct spherical aberration
- Aberrometry was used to study the surface wetting and drying of contact lenses.

ZERNIKE NORMS – NEED TO BE REMEMBERED

- (Refer to OCO reference tables)
- Know the following Zernike modes, their Z designation and shapes
- Second-order aberrations
- Third-order aberrations
- Spherical aberration (middle of the five fourth-order aberrations)
- Know the mean HO RMS value for a 6.0-mm pupil

SELECTED READING/REFERENCES

- Salmon TO, van de Pol C. **Evaluation of a clinical aberrometer for lower-order accuracy and repeatablity, higher-order repeatability and instrument myopia**. Optom J Am Opt Assoc 2005;76:461-72.
- Rodriguez PN, Gonzalez L, Hernandez JL. **Accuracy and reproducibility of Zywave, Tracey, and experimental Aberrometers**. J Ref Surg 2004;20:810-817
- Salmon TO, West RW, Gasser W, Kenmore T. **Measurement of refractive errors in young myopes using the COAS Shack-Hartmann aberrometer**. Optom Vis Sci 2003;80:6-14
- Cheng X, Himebaugh NL, Kollbaum PS, Thibos LN, Bradley A. **Validation of a clinical Shack-Hartmann aberrometer**. Optom Vis Sci 2003;80:587-595
- Moreno-Barriuso E, Marcos S, Navarro R, Burns SA. **Comparing laser ray tracing, the spatially resolved refractometer, and the Hartmann-Shack sensor to measure the ocular wave aberration**. Optom Vis Sci 2001;78:152-156
- Salmon TO, Thibos LN, Bradley A. **Comparison of the eye's wave-front aberration measured psychophysically and with the Shack-Hartmann wave-front sensor**. J Opt Soc Am A Opt Image Sci Vis 1998;15:2457-2465
- Amano SA, Yamagami S, Miyai T, Miyata K, Samejima T, Oshika T. **Age-related changes in corneal and ocular higher-order wavefront aberrations**. Am J Ophthalmol 2004;137:988-992
- Cheng H, Barnett J, Vilupuru A, et al. **A population study on changes in wave aberrations with accommodation.** J Vision 2004;4:272-280
- Brunette I, Bueno JM, Parent M, Hamam H, Simonet P. **Monochromatic aberrations as a function of age, from childhoodto advanced age**. Invest Ophthalmol Vis Sci 2003;44:5438-5446
- Wang L, Koch DD. **Ocular higher-order aberrations in individuals screened for refractive surgery**. J Cataract Refract Surg 2003;29:1896-1903
- Thibos LN, Bradley A, Hong X. **A statistical model of the aberration structure of normal, well-corrected eyes**. Ophthalmic Physiol Opt 2002;22:427-433
- Thibos L, Hong X, Bradley A, Cheng X. **Statistical variation of aberration structure and image quality in a normal population of healthy eyes**. J Opt Soc Am A 2002;19:2329- 2348
- Castejon-Mochon JF, LopezGil N, Benito A, Artal P. **Ocular wave-front aberration statistics in a normal young population**. Vis Res 2002;42:1611-1617
- Porter J, Guirao A, Cox I, Williams DR. **Monochromatic aberrations of the human eye in a large population**. J Opt Soc Am A 2001;18:1793-1803
- ANSI. **American National Standard for Ophthalmics—Methods for reporting optical aberrations of eyes**: ANSI, 2004
- Thibos L, Applegate R, Schwiegerling J, Webb R, Members VST. **Standards for Reporting the Optical Aberrations of the Eye**. In: Lakshminarayanan V, editor. **Vision Science and Its Applications**. Santa Fe, NM: Optical Soc Am, 2000:232-244
- Atchison D, Scott D, Cox M. **Mathematical Treatment of Ocular Aberrations: a User's Guide**. In: Lakshminarayanan V, editor. **Vision Science and Its Applications**. Santa Fe, NM: Optical Soc Am, 2000: 110-130
- Campbell CE. **Matrix method to find a new set of Zernike coefficients from an original set when the aperture radius is changed**. J Opt Soc Am A 2003;20:209-217
- Schwiegerling J. **Scaling Zernike expansion coefficients to different pupil sizes**. J Opt Soc Am A 2002;19:1937-1945
- Ginis HS, Plainis S, Pallikaris A. **Variability of wavefront aberration measurements in small pupil sizes using a clinical Shack-Hartmann aberrometer**. BMC Ophthalmol 2004;4:1
- Campbell C. **A New Method for Describing the Aberrations of the Eye Using Zernike Polynomials**. Optom Vis Sci 2003;80:79-83
- Thibos L. **The chromatic eye: a new reduced-eye model of ocular chromatic aberration in humans**. Appl Optics 1992;31:3594-3600
- Levy Y, Segal O, Avni I, Zadok D. **Ocular higher-order aberrations in eyes with supernormal vision**. Am J Ophthalmol 2005;139:225-228

SELECTED READING/REFERENCES (CONT.)

- Zadok D, Levy Y, Segal O, Barkana Y, Morad Y, Avni I. **Ocular higher-order aberrations in myopia and skiascopic wavefront repeatability**. J Cataract Refract Surg 2005;31:1128-1132
- Netto MV, Ambrosio R Jr., Shen TT, Wilson SE. **Wavefront analysis in normal refractive surgery candidates**. J Refract Surg 2005;21:332-338
- Artal P, Ferro M, Miranda I, Navarro R. **Effects of aging in retinal image quality**. J Opt Soc Am A 1993;10:1656-1662
- Guirao A, Gonzalez G, Redondo M, Geraghty E, Norrby S, Artal P. **Average optical performance of the human eye as a function of age in a normal population**. Invest Ophthalmol Vis Sci 1999;40:203-213

  Calver RI, Cox MJ, Elliot DB. **Effect of aging on the monochromatic aberrations of the human eye**. J Opt Soc Am A 1999;9:2069-2078
- McClellan JS, Marcos S, Burns SA. **Age-related changes in monochromatic wave aberrations of the human eye**. Invest Ophthalmol Vis Sci 2001;42:1390-1395
- He JC, Sun P, Held F, Thorn F, Sun X, Gwiazda JE. **Wavefront aberration in eyes of emmetropic and moderately myopic school children and young adults**. Vis Res2002;42:1063-1070
- Artal P, Berrio E, Guirao A. **Contribution of the cornea and internal surfaces to the change of ocular aberrations with age**. J Opt Soc Am A 2002;19:137-143
- Wang L, Santaella RM, Booth M, Koch DD. **Higher-order aberrations from the internal optics of the eye**. J Cataract Ref Surg 2005;31:1512-1519
- Applegate RA, Ballentine C, Gross H, Sarver EJ, Sarver CA. **Visual acuity as a function of Zernike mode and level of root mean square error**. Optom Vis Sci. 2003 Feb;80(2):97-105
- Applegate RA, Sarver EJ, Khemsara V. **Are all aberrations equal?** J Refract Surg. 2002 Sep-Oct; 18(5):S556-62
- Applegate RA, Marsack JD, Ramos R and Sarver EJ. **Interaction between aberrations to improve or reduce visual performance**. 2003. Journal of Cataract & Refractive Surgery 29 (8): 1487-1495
- Thibos, L. N., Hong, X., Bradley, A., & Applegate, RA. **Metrics of optical quality of the eye. 2004**. Journal of Vision