Methods for reporting aberrations of eyes
ANSI Z80.28:2004

A common language for a special community
New Capabilities for Measuring Ocular Aberrations Call for a New Way to Describe Aberrations to One Another

- Ways to classify and quantify aberrations
- Common notation
- Common ways to communicate results
Clear Communications Through Standardization

- 1999 - OSA task force formed
- 2000 - OSA task force issues “Standards for Reporting the Optical Aberrations of Eyes”
- 2002 - ANSI Z80 forms committee to create a U.S. national standard based on the OSA standard
- 2002 - ANSI Z80.28 - Methods for reporting optical aberrations of eyes - authorized and work begins
- 2004 - ANSI Z80.28 becomes an American National Standard
The committee

Ray Applegate
Charlie Campbell
Larry Horowitz
Scott MacRea
Dan Neal
Ed Sarver
Jim Schwiegerling
Larry Thibos
Rob Webb
Issues to Address

• Zernike polynomial representation of aberrations
  • Notation
  • Normalization
  • Coordinate system
  • Aperture size
  • Centration
Issues to Address

• Display of aberrations
  • Zernike coefficients
  • Wavefront error contours maps
Issues to Address

• Comparison of measurements
  • equivalency of aberrometers
  • test devices

Still an open issue
Issues to Address

• Communication of results
  • Zernike coefficients
  • alternate methods
Issues to Address

- Information on using Zernike polynomials
- Calculation of coefficient using aberrometer data
- Accounting for rotation and translation of the coordinate system
- Accounting for changes in pupil size
- Conversion from non-standard Zernike notation
- Mathematical forms of the Zernike polynomials with their common names
Several authors, authorities - each with a different notation – something of a mess

- Zernike notation
- Malacarra
- Noll
- Zemax
- U of Arizona
- OSA
- Born & Wolf
- U of Arizona
- ISO
- $\mathbb{U}_{30}$
- $\mathbb{Z}_6$
- $\mathbb{Z}_9$
- $\mathbb{Z}_{11}$
- $\mathbb{Z}_3^3$
- $\mathbb{Z}_3^3$
- $\mathbb{U}_3^3$
Two index notation method

- Zernike functions are specified by 2 indices
  - $n$ - the radial index
  - $m$ – the meridional index

Notation of choice - $Z_{n}^{m}$

Alternate notation $Z(n,m)$
Single index notation

• Best thought of as an ordering method

\[ Z_j \quad \text{where:} \quad j = \frac{n(n + 2) + m}{2} \]
Single or Double Index?

$Z_9$ ?

$Z_{12}$ ?

$Z_{15}$ ?
Single or Double Index?

\[ Z_{9} = Z_{3}^{3} \]

\[ Z_{12} = Z_{4}^{0} \]

\[ Z_{15} = Z_{5}^{-5} \]
Zernike Coefficient Normalization

- Zernike functions have 3 terms
  - Normalization $N_n$
  - Radial $R(\square)_n^{\mid m\mid}$
  - Meridional $M(m\square)$

$$Z_n^m(\square, \square) = N_n R(\square)_n^{\mid m\mid} M(m\square)$$

The value $N$ must be chosen
Zernike Coefficient Normalization

- If \( N \) is chosen to equal 1, the coefficients are said to be “un-normalized”
- If \( N \) is chosen to equal \( \sqrt{(2 \pi m_0)(n + 1)} \), the coefficients are said to be normalized and -

The square root of the sum of the squares of the coefficients is equal to the RMS wavefront error

Choice - Normalized
Zernike Coordinate System

Zernike polynomials raised in astronomy find themselves in ophthalmic optics where things are a little different – to say the least
Coordinate systems

• Astronomers
  Geographers
  Sailors

• Mathematicians
  Physicists
  Ophthalmic professions
  - ISO 8429:1986

Choice - Ophthalmic
• Changing aperture size changes coefficient values for the same wavefront

Green bars = 4 mm pupil
Red bars = 6 mm pupil
Centration

• A change in coordinate center changes Zernike coefficient values

Choice – \textit{Pupil center}
Centration

• A change in coordinate center changes Zernike coefficient values

Choice – *Pupil center*

Green - centered

Red - decentered 0.5 mm
Centration

- A change in coordinate center changes Zernike coefficient values

Choice – *Pupil center*

Green - centered

Red - decentered 0.5 mm
Effects of de-centered corrections

• The original errors are completely corrected
• New aberrations are introduced
• Each original Zernike term introduces terms of lower order
• The magnitude of the introduced aberrations are proportional to the magnitude of the original term and to the magnitude of de-centration
• Example – de-centered sphere and cylinder (2nd order) introduce prism (tilt – 1st order)
Presentation of wavefront information

• How can we present wavefront information in an intelligible, uniform manner?
Zernike Coefficient Lists

- Include the aperture radius used to create the coefficients expressed in millimeters
- Use normalized coefficients expressed in microns of wavefront error
- List coefficients in standardized single index order
- Label coefficients with standardized double index Zernike symbols

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<th>aperture</th>
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Displays from various wavefront refractors
ANSI Unified Scale

- Wavefront value equals zero at the pupil center
- 21 color incremental scale - red most positive error, green zero error - blue most negative error
- Standardized scale increments - 0.1, 0.2, 0.5, 1.0 microns
- Pupil center marked with diameter and meridians indicated
ANSI Unified Scale
Communication of results

• Communication of Zernike coefficients
  – Single index ordered list starting with aperture radius, aperture in mm, normalized coefficients in microns

• Deflection information
  – 2 gradient position arrays in mm with a coordinate system with the pupil center as its origin
  – 2 gradient component arrays
What you will find in ANSI Z80.28 - Standardized items

- Standardized definitions and terms with particular attention to Zernike polynomial functions
- Standardized coordinate system definition
- Standardized methods of communicating wavefront information in the form Zernike coefficient sets, wavefront error gradients and wavefront errors
- Standardization of wavefront error displays
What you will find in ANSI Z80.28 - Useful information

- Information on creating Zernike coefficient sets from wavefront gradient data
- Information on compensating wavefront information as pupil size, centration and orientation change
- A list of Zernike polynomial functions with their mathematical forms and common names
- Information on converting non-standard Zernike coefficient sets to the standard form
Topics for future work

• Inclusion of new visual metrics that fully use the new information available in a clear, clinically relevant fashion
• Presentations of point spread functions
• Standardization of the aberrometers themselves
Our goal is Clear Communication!!

• Not just between you and your staff
• Not in a hard to understand insider code
• The goal is easy transparent exchange of relevant information to anyone of reasonable intelligence
• This includes patients, clinical colleagues, research colleagues,
5th International Congress of Wavefront Sensing & Optimized Refractive Corrections
February 21-23, 2004 – Whistler, Canada