Wavefront Error and Visual Performance

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Once the wavefront error is determined, image quality is defined.
To understand wavefront error it is useful to change our thinking from rays of light to waves of light.
Rays
Wavefront after refraction
Waves and Rays

Ideal

Aberrated

© RAA
Waves and Rays

Ideal

Aberrated
A particularly useful representation of wavefront error is to fit the error between the actual wavefront and the ideal wavefront with a Zernike expansion.
Fitting the error data with a Zernike expansion parcels the error into unique building blocks.
\[ Z(r^n, f \theta) = Z_n^m \]

- \( n = \text{radial order} \)
- \( m = \text{angular frequency} \)

Sine phase  \( \rightarrow \)  Cosine phase
\[ Z(r^n, f \theta) = Z_n^m \]

- \( n = \) radial order
- \( m = \) angular frequency

Sine phase: 2, 6, 10
Cosine phase: 3, 7, 11
Each weighted Zernike mode when added together form a representation of the actual WFE.
Machines to measure wavefront error are available today from a variety of sources and generally look very much like corneal topography units.
Wavefront error degrades the optical image it cannot improve image quality above the diffraction limit.
3mm pupil
Typical non-surgical eye
Best spectacle correction

WFE = 0.041 µm

3mm pupil Post LASIK >1yr
Happy patient 20/15 acuity
Best spectacle correction

WFE = 0.133 µm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg
Wavefront error defines the ideal compensating optic.
WFE specifies how much tissue or material to remove at every location across the pupil.
WFE specifies how much tissue or material to remove at every location across the pupil.

Wavefront retarded: Remove more material
WFE specifies how much tissue or material to remove at every location across the pupil.

Wavefront advanced:
Remove less material
Amount of material to remove = \frac{C + WFE}{n' - n}

Where:
- C = minimum amount of tissue to be removed
- WFE = wavefront error
- n' = optical index of the material light is entering
- n = optical index of the material light is leaving
But do higher order aberrations really matter?

- It depends on their magnitude.
- It depends on the pupil size
- It depends on our neural transfer function
- It depends on the visual task
- It depends on the object
Magnitude

For many clinical eyes that we have thrown into the garbage bag of irregular astigmatism, it is very important.
Pupil Size

For normal eyes the potential gains are significant for large pupil sizes and diminish as the pupil size gets small.
To understand impact of aberrations on visual performance it is very helpful to know which aberrations are particularly bad and how they interact with each other.
Equally important to researchers and clinicians alike is the development of single value metrics of optical quality capable of predicting visual performance.
An important feature of the normalized Zernike expansion is that the magnitude of the coefficient for each mode reflects its relative contribution to the total wavefront error.
JH 09/28/00 6mm pupil Post LASIK >1yr

Wavefront Zernikes
Just because the magnitude of the coefficient reflects its relative contribution to the total wavefront RMS error does not mean that the largest Zernike coefficient will affect vision the most.
Different modes of the Zernike expansion affect vision more than others.
Further, modes can combine to lessen the adverse visual effects or combine to further worsen visual performance.
Wavefront error fundamentally defines the optical properties of the eye and can be used to calculate other metrics of optical quality.
Fourier Transform

Wavefront error
PSF

Higher-order aberrations

Sph  0.74 D
Cyl -0.63 D
Axis  8°
LO RMS  0.35 μm
HO RMS  0.24 μm
TOT RMS  0.43 μm
Pupil  4.00 mm
Wavelength  546 nm

2D PSF

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Astigmatism  Defocus  Astigmatism
Trefoil     V. Coma     H. Coma     Trefoil
Quadrafoil  2nd Astigmatism  Spherical  2nd Astigmatism  Quadrafoil
Pentafoil  2nd Trefoil  2nd V. Coma  2nd H. Coma  2nd Trefoil  Pentafoil
Such a transformation is a powerful tool for visualizing and quantifying the impact of aberrations on visual performance.
Notice in the following simulations that as the pupil size decreases WFE decreases despite the fact that the dioptric defocus remains constant.
Further, notice in the simulations that measuring wavefront error for a large pupil and comparing it to visual performance measured through a smaller pupil leads to erroneous conclusion.
To determine how ocular wavefront error affects visual performance one must measure both at the same pupil size.
Defocus = 0.25 D; RMS WFE = .58 µm

Pupil Diameter = 8.00 mm
Defocus = 0.25 D; RMS WFE = 0.32 µm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 6.00 mm
Defocus = 0.25 D; RMS WFE = 0.14 µm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 4.00 mm
Defocus = 0.25 D; RMS WFE = 0.036 µm

Image Simulation
View D: 4.0000 ft, Height: 0.8437 in, Angle: 1.0070 deg

Pupil Diameter = 2.00 mm
Wavefront error tells us that the image is getting better. Dioptic error does not.
While we have demonstrated that visual acuity decreases with increasing wavefront error for any single mode…

OVS in press.
we have also reported that all aberrations are not equal...

and that aberrations interact to increase or decrease visual performance.

JCRS in press
$$Z(r^n, f \theta) = Z_n^m$$

$n =$ radial order

$m =$ angular frequency

sine phase

© RAA
Predicted Letters Gained or Lost

<table>
<thead>
<tr>
<th>Zernike Coefficient</th>
<th>2nd Order</th>
<th>3rd Order</th>
<th>4th Order</th>
<th>Sphere &amp; Cylinder</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>

UUHH
RAARAA
HC Letters Gained or Lost

Equivalent Diopters = 0.19 D
Equivalent Diopters = 0.19 D
Zernike terms interact to affect visual performance.
\[ Z(r^n, f \theta) = Z_n^m \]

- \( n \) = radial order
- \( m \) = angular frequency

\[ \text{sine phase} \quad \longleftrightarrow \quad \text{cosine phase} \]
\[ \sqrt{0.2^2 + 0.15^2} = 0.25 \]

RMS in \( \mu \)
The SSCP Matrix is singular.
So if wavefront error and equivalent diopters do not serve well to explain the variations in visual performance, is there something better?
Regression Plot

Inclusion criteria: Total RMS is .25 from Metrics Data.svd

\[ Y = -12.764 + 12.029 \times X; \quad R^2 = .263 \]
Regression Plot
Inclusion criteria: Total RMS is .25 from Metrics Data.svd

\[ Y = -9.887 + 6.031 \times X; \ R^2 = .494 \]
In addressing this question, it is important to remember that retinal image quality is the first step in the visual process.
Camera optics

Film

Developing

Enlarging Optics and Printing

Eye’s optics

Photoreceptors

Neural Processing

Visual Percept

The Mind’s Eye
Camera optics

Film

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The measurement of the wavefront error of the eye provides the best possible assessment of the retinal image quality.
It does not tell us how the brain transfers the image into a visual percept.
None-the-less, we do have good estimates of the neural transfer function in the typical normal eye.
Figure 7-9 from MacRae, Krueger and Applegate, *Customized Corneal Ablation: The Quest for Super Vision*, Slack, Inc. 2001.
Regression Plot

Inclusion criteria: Total RMS is .25 from Metrics Data.svd

Dioptric equivalent of 0.19 D

\[ r = 0.85 \]

\[
Y = -12.107 + 19.827 \times X; R^2 = .719
\]
Regression Plot

Inclusion criteria: Total RMS is .25 from Metrics Data.svd

\[ Y = -12.107 + 19.827 \times X; \ R^2 = .719 \]
Finally, it is wise to remember that even if we know the optical and neural transfer functions of the eye we do not always know how the mind’s eye will interpret the information.
All Is Vanity, By Gilbert
All is Vanity, By Gilbert
In Summary

• New clinically viable aberrometers are changing the way we correct the refractive errors of the normal and clinical eye.
• Zernike modes interact to increase or decrease visual perception.
• Pupil size plays an important role in visual perception.
• To compare the affects of aberrations on visual performance both have to be measured at the same pupil size.
In Summary

• The best visual image and best visual perception occurs when aberrations are minimized.

• New single parameter metrics calculated from wavefront error can be used to predict visual performance measures like acuity.
The animation, simulations, and graphics of WFE in this presentation were generated using a program call CTView.

www.sarverassociates.com
The eye graphics in this presentation were generated using a program call EyeView.

www.sarverassociates.com
Thank you