January 26-29 2006
Atlantis Hotel, Paradise Island, Bahamas
The Difference Between Corneal Topography and Wavefront

The International Congress of Wavefront Sensing & Optimized Refractive Corrections

Wavefront Basics Course
January 26, 2006

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Disclosure

- Consultant to Bausch & Lomb
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- Consultant to Reichert
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Wavefront vs Topography:

Conceptually

Technically

Clinically
Wavefront vs Topography

Wavefront tells you the origin and destination

Shape (topography) tells you the mechanism
Function vs Shape

Which is Better?
Wavefront vs Topography

4 dimensional surface vs 3 dimensional surface

3-Space and time vs 3-Space

Once captured:

3-Space vs 3-Space

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Anatomic Comparison

- **Corneal Topography**
  - Anterior Surface Only
  - Cannot provide information on internal optical surfaces

- **Total Ocular Wavefront**
  - Whole Eye Information
  - Cannot provide information about individual structures in the eye or isolate the source of aberrations
Coma

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Tools for Analysis

- Zernike
- Fourier
- Conic Section
Tools for Analysis

- Zernike - often used for function
- Fourier
- Conic Section – often used for shape
Periodic Table of the Zernike Polynomials

Zernike notation
What is a Mathematical Decomposition or Reconstruction?

Figure provided by Dr. Scott MacRae

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What does “order” mean?

- Higher “order” means faster spatial rate of change
- Applies to BOTH Topography AND Wavefront
For Which Surfaces Can I Use Zernikes?

ANYTHING YOU WANT!!

- Corneal Surface - yes!
- Corneal Wavefront - yes!
- Optical Wavefront - yes!
Do Zernikes derived from the Corneal Wavefront Correlate to those from the Corneal Surface?

■ YES!

■ With almost a perfect one-to-one correspondence, depending on the reference

■ Spherical Aberration is the most sensitive term with respect to change of reference

Mahmoud, Roberts, ARVO 2006
What if the Analysis Techniques are Different?

- Corneal Surface vs Corneal Wavefront
- Corneal Surface vs Ocular Wavefront

BE CAREFUL!
What is a Conic Section?

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Conic Constants

- Aspheric parameters: Q, E and p, as well as eccentricity, e
  - All are mathematically related to each other

- Defines how different from a sphere is the conic section
  - Surface is spherical if Q = 0, E = 0, p = 1, or e = 0

- How “accurate” it is depends on how well the actual surface conforms to a conic section
Why use a Conic Section?

- Mathematically Tractable
- Convenient
Is the cornea similar to a Conic Section?

- Pre-op – pretty good approximation
- Post-op - NO
How do you fit a conic section?

- **2-dimensionally**
  - Each meridian or two principal meridians could be fit.
  - Each “fit” meridian would have its own constant

- **3-dimensionally**
  - Surface of revolution is fit to whole cornea
  - One conic constant for the whole surface

- Sphere
- Oblate Ellipsoid
- Prolate Ellipsoid

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Pre-Operative Topography

\[ E = 0.37; R_0 = 7.62 \text{ mm} \]

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Post-LASIK – “oblate shape”

$E = -0.91; R_o = 8.54$ mm

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Post-LASIK – “prolate shape”

E = 0.23; R_o = 7.75 mm

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Average Pre-op Shape of 2,380 eyes

Average Pre-op Q = -0.144 or Prolate

Clinical data from the Hong Kong Sanatorium and Hospital

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Which one is Prolate and which Oblate?

Are these post-op shapes conic sections?

Clinical data from the Hong Kong Sanatorium and Hospital

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What is the Most Important Surface Feature Optically?

Average of 1485 Prolate Post-op eyes
mean $Q = -0.093$ (max neg $= -0.41$)

and 895 Oblate eyes
mean $Q = 0.062$ (max $0.25$)

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**Does “Prolate” = Good Optics??**

Tuan, et al, American Academy of Optometry, 2004, demonstrated NO correlation of prolate vs oblate, or asphericity to quality of vision, either pre-operatively or post-operatively.
What are some Common “Prolate” Shapes?

- Central Keratoconus
- Central Island

Are these Good Optics?
For Which Surfaces Can I Use Conic Constants?

ANYTHING YOU WANT!!

- Corneal Surface - yes!
- Corneal Wavefront - yes!
- Ocular Wavefront - yes!
For Which Surfaces Can I Use Conic Constants?

ANYTHING YOU WANT!!

- Corneal Surface - yes!
- Corneal Wavefront - yes!
- Ocular Wavefront - yes!
Zernike vs Conic Section

18 terms (2\textsuperscript{nd} – 5\textsuperscript{th} order)

2 terms, no matter how you slice it!

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2 terms for astigmatism vs 0 terms for astigmatism

18 terms (2\textsuperscript{nd} – 5\textsuperscript{th} order)

2 terms,
no matter how you slice it!

Sphere, oblate ellipsoid, prolate ellipsoid

Central curvature and Asphericity
Or
Major and Minor Axis

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Good for Irregularies vs ONLY Regular Surfaces

18 terms (2nd – 5th order)

2 terms, no matter how you slice it!

Sphere  oblate ellipsoid  prolate ellipsoid

Central curvature and Asphericity

Or

Major and Minor Axis

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Post-Op Refractive Surgery

Does it make sense to analyze the optical wavefront with 18 terms, while the corneal surface, which produced 100% of the surgically-induced changes in that wavefront, with only 2 terms?
Prospective Masked Study

- Contralateral Eye Study with strict enrollment criteria
- One eye treated with Laser 1 and one with Laser 2
  - N = 30
  - Treatment Eye Randomized
  - Dr. Richard Lembach

Twa, et al., AJO 2005
6 Months – Shape Analysis
Repeated Measures Analysis of Variance
Higher Order Spherical Aberration Terms

Statistically significant change in 4\textsuperscript{th} order (p<0.0001) topographic spherical aberration

Statistically significant change in 8\textsuperscript{th} order (p<0.0022) topographic spherical aberration

Significant interaction term between outcome and laser (p<0.0001 for 4\textsuperscript{th} order and p<0.0061 for 8\textsuperscript{th} order)

Laser 2 induced significantly greater change in the spherical aberration terms than Laser 1

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6 Months
Spherical Aberration from Wavefront Analysis

Laser 2 induced significantly greater spherical aberration than Laser 1
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Bausch & Lomb Technolas 217, OZ = 6.5mm
VISX S3, OZ = 6.5mm

Average of n= 30 post-op maps
Optical Zone = 6.5mm
Ablation Zone to 9mm

Contralateral Eyes at 6 months post-op

Twa, et al., AJO 2005

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Asphericity vs Curvature Gradient

Pre-op

- No difference in Asphericity or Curvature Gradient between eyes

n = 30
LASER 1

n = 30
LASER 2
Asphericity vs Curvature Gradient
6 Months Post-Op

- No difference in Asphericity with either 4mm or 6mm fitting regions
- Significant difference in Curvature Gradient

Laser 1, curvature gradient = 0.9
Laser 2, curvature gradient = 1.6

- The group with the higher curvature gradient also had greater spherical aberration induction measured by optical wavefront

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Aberrations vs Shape Features

Aberrations from Wavefront:

- Zero Order - piston
- First Order – tilt
- Second Order – Sphere and Cylinder
- Higher Order - including Spherical Aberration

Shape from Topography:

- Zero Order – elevation
- First Order – slope
- Second Order – curvature, toricity
- Higher Order – "Curvature Gradient"
PRE OP

Laser 1

vs

Laser 2

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POST OP

Laser 1
Vs
Laser 2

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Pre-Op vs Post-Op

- **Pre-op**
  
  Lower order analysis adequate most of the time.

- **Post-op**
  
  Lower order analysis of both shape and optical aberrations is **NOT** adequate most of the time.
Periodic Table
of the Zernike Polynomials
Zernike notation
Original and 5th order Zernike reconstruction of Corneal Topography

4th order cannot adequately represent spherical aberration

Mahmoud, et al., The Impact of Zernike Order in Representing Spherical Aberrations After LASIK ARVO, 2003

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Adding the 6\textsuperscript{th} and 8\textsuperscript{th} order spherical aberration terms dramatically improves the reconstruction of the original profile.

BOTH the 5\textsuperscript{th} order reconstruction and 8\textsuperscript{th} order reconstruction have the SAME 4\textsuperscript{th} order spherical aberration.
Spatial Resolution

- Topography - Thousands of points
- Wavefront Sensors - Hundreds of Points

Spatial Resolution limits the Zernike Order that can be Calculated
Region of Measurement

- Topography - 8 to 10mm of coverage
- Wavefront Sensors - limited by the pupil

Important Information necessary to Analyze Corneal Biomechanical Response exists outside the pupil

Saturday Presentation
Which is More Important in Refractive Surgery?

Shape of the Cornea or Function of the Eye?
Shape:

- The Laser is NOT programmed with visual acuity
- The Laser is NOT programmed with refractive error
- The Laser is NOT programmed with wavefront error
Shape:

- The Laser is NOT programmed with visual acuity
- The Laser is NOT programmed with refractive error
- The Laser is NOT programmed with wavefront error

- Refractive Error or Wavefront Error is converted to a depth profile based on a specific formula.
  - Refractive Error: Munnerlyn
  - Wavefront Error: Optical Path Difference
Shape:

- The Laser is NOT programmed with visual acuity
- The Laser is NOT programmed with refractive error
- The Laser is NOT programmed with wavefront error

- Refractive Error or Wavefront Error is converted to a depth profile based on a specific formula.
  - Refractive Error: Munnerlyn
  - Wavefront Error: Optical Path Difference

- The Laser IS programmed with a SHAPE profile.

SHAPE is the TARGET!!

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What is the “Ideal” Corneal Shape?

????????
What is the “Ideal” Corneal Shape?

????????

The one that produces the optimal wavefront!

Topography cannot provide information on the spherical component of refraction
Topography-Guided and Wavefront-Guided

- Role of Wavefront Analysis
  - Characterize performance of the entire optical system of the eye
  - FUNCTION

- Role of Corneal Topography
  - Characterize mechanism and understand functional results
    (Saturday, 8:40am – more details)
  - SHAPE
Is Either One Sufficient Alone?

NO!!
Wavefront and Topography

TWO SIDES OF THE SAME COIN
Thank you!
Spatial Resolution
Laser 1

100x100

10 x 10, 5\textsuperscript{th} order

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Laser 1

100x100

25 x25, 5th order

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Laser 2

100x100

10x10, 5\textsuperscript{th} order

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Laser 1

- 5th order
- 10 x10
Laser 1

- 6th order
- 10 x 10
Laser 1

- 7th order
- 10 x 10
Laser 1

- 8th order
- 10 x 10
Laser 1

- 9th order
- 10 x 10
Laser 1

- 10\textsuperscript{th} order
- 10 \times 10
Limit Conic Section Fit to central cornea?

- When do patients have complaints?
  - At night when the pupil is large
  - NOT in the daytime when the pupil is small

- Post-op maps do not conform to conic sections