What’s New in Ocular Biomechanics?

The International Congress of Wavefront Sensing & Optimized Refractive Corrections

Wavefront Course
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Disclosure

- Consultant to Bausch & Lomb
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Why are Corneal Biomechanics Important?

- Scientific Curiosity?
- Improve Prediction of Refractive Outcomes?
- Identify patients at risk for ectasia?
- Accurate measurement of IOP?
- Other new ideas?
Intra-Ocular Pressure (IOP)

What do we KNOW?

- Measured IOP decreases after refractive surgery - WHY????
  - Decrease in curvature and thickness???
LASIK for Myopia and Myopic Astigmatism
Pre-Op and 3 Month post-op IOP

- \( N = 8,113 \)
- mean diff IOP \( \sim -2\text{mmHg} \)
- mean diff sph equiv \( \sim -5\text{diopters} \)
- \( R^2 = 0.009 \)
- \( P < 0.001 \)
- Slope = \(-0.12\text{mmHg/diopter}\)

Chang and Stulting, Ophthalmology, 2005.
LASIK for Myopia and Myopic Astigmatism Pre-Op and 3 Month post-op IOP

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Sources of Error in Applanation Tonometry

- Gold Standard: Goldman Tonometry
  - Assumptions were made with Corneal Curvature, Corneal Thickness, and Corneal Biomechanical Properties
The flatter the cornea, the lower the measured pressure.

The steeper the cornea, the higher the measured pressure.

Potential Error LOW

Liu and Roberts, JCRS, January 2005
Effect of Corneal Thickness - ALONE

- The thicker the cornea, the higher the measured pressure.
- The thinner the cornea, the lower the measured pressure.
- Potential Error - Moderate

Liu and Roberts, JCRS, January 2005
The “stiffer” the cornea, the greater the measured pressure.

The “softer” the cornea, the lower the measured pressure.

Potential Error – HUGE - > 10mm

Liu and Roberts, JCRS, January 2005
Can IOP Measurement be corrected by a simple conversion based on thickness?

- NOT ACCURATELY!!
  - What about thick, soft corneas (ex. Fuchs’) and thin, stiff corneas?

- Which parameters dominate the measurement artifact?
  - Theory predicts Biomechanical Properties dominate!!
  - Change in measured IOP after refractive surgery is likely driven by a fundamental modification in properties, rather than a simple change in thickness.

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Can Biomechanical Properties be Measured?

Finally!!

Reichert Ocular Response Analyzer

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Applanation Detection
Applanation Detection II

Air-jet

Applanated Cornea
Applanation Signal Plot

- **Applanation Signal**
- **Pressure (air pulse)**

- **“In” Signal Peak**
- **Applanation Pressure 1**
- **Hysteresis**
- **“Out” Signal Peak**
- **Applanation Pressure 2**
Visco-Elastic System
An Automotive “Strut” Assembly

- Coil Spring: Static Resistance (Elasticity). strain (deformation) is directly proportional to stress (applied force), independent of the length of time or the rate at which the force is applied.

- Shock Absorber: Viscous Resistance (Damping). The resistance to an applied force depends on the speed at which the force is applied, and the length of time over which it is applied.
Normals, Keratoconus, Fuchs’

Slide provided by Reichert

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The Normal Cornea

Crosslinks (x):
- antero-peripheral distribution
- interlamellar cohesion
- couple PST & central curvature

Stroma = fibers vs matrix
A Mechanical Model of Keratectomy-Induced Flattening

PRE-ABLATION

POST-ABLATION:

- Crosslinks (x):
  - antero- peripheral distribution
  - interlamellar cohesion
  - couple PST & central curvature

- Stroma = fibers vs matrix

- Ablation ⇒ relaxation
  and peripheral stromal thickening (PST)

William Joseph Dupps, M.D., Ph.D.

Cynthia Roberts, Ph.D.
Biomechanical **Central Flattening** and **Peripheral Steepening**

- **Enhances** a Myopic Procedure
- **Reduces** the effect of a Hyperopic Procedure
- Flattening (hyperopic shift) in a “non-refractive” PTK
  - Including the PTK profile in one axis of an astigmatic procedure
- **Induces unintended para-central and peripheral shape changes** that result in **aberrations**!!

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Pre / Post Lasik Corneal Hysteresis

Luce, JCRS, 2005

Cynthia Roberts, Ph.D.
What is the Impact of Corneal Biomechanical Properties?

- Induce **variability** of Second Order Outcomes (central flattening of varying amounts)

- **Induce** higher order aberrations (paracentral and peripheral steepening)

- Induce **variability** of higher order aberration induction, most prominently, spherical aberration

- Induce **artifacts** in the measurement of IOP (Alter the fundamental biomechanical properties!)

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Can Biomechanical Response be Manipulated?
From John Marshall, Ph.D.  

Cynthia Roberts, Ph.D.
Biomechanics of Optical zone size

- Decreased variability and improved PREDICTABILITY with increased zone size………

- This is NOT an optical phenomenon…

- It is a BIOMECHANICAL phenomenon!!
  - Individual Variability of Biomechanical Properties!!
A Mechanical Model of Keratectomy-Induced Flattening

- **Stroma** = fibers vs matrix
- Ablation ⇒ relaxation and peripheral stromal thickening (PST)
- Crosslinks (x):
  - antero-peripheral distribution
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PRE-ABLATION

POST-ABLATION:

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Contralateral Eye Studies

- Biomechanical properties matched between eyes
- Analyze the differences in response between eyes
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
Spherical Aberration from Wavefront Analysis

Laser 2 induced significantly greater spherical aberration than Laser 1
6 Months – Shape Analysis
Repeated Measures Analysis of Variance
Higher Order Spherical Aberration Terms

Statistically significant change in 4th order (p<0.0001) topographic spherical aberration

Statistically significant change in 8th order (p<0.0022) topographic spherical aberration

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

Laser 2 induced significantly greater change in the spherical aberration terms 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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The Transition Zone is NOT Neutral!!

WHEREVER ablation occurs, corneal structure is altered and the shape is modified
Difference in Spherical Aberration Induction Cannot be Explained by Loss of Ablation Efficiency due to the Contralateral Study Design
Shape Metrics for Analyzing Biomechanical Response
Aberrations vs Shape Features

- **Aberrations from Wavefront:**
  - Zero Order - piston
  - First Order – tilt
  - Second Order – Sphere and Cylinder
  - Higher Order - including Spherical A

- **Shape from Topography:**
  - Zero Order – elevation
  - First Order – slope
  - Second Order – curvature, toricity
  - Higher Order – "Curvature Gradient"
Post-LASIK – “oblate shape”

E = -0.91; R_o = 8.54 mm

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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

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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 sensor

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PRE OP

Laser 1
n=30

vs

Laser 2
n=30
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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.

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Biomechanical Response

- This is a higher-order, multi-dimensional response, and higher-order, multi-dimensional analysis methods are required.

- Simple thickness and curvature change compensation cannot provide individual correction factors in the measurement of IOP.

- Aspheric factors don’t tell the whole story in spherical aberration induction.
Ectasia – what do we know?

- Incidence is quite small out of total number of procedures performed.

- Correlates with low residual stromal bed thickness. However, has occurred with more than adequate bed.

- Can be associated with suspicious curvature patterns pre-op. Some patients with similar patterns do well after LASIK.

- Remains difficult to predict!
Is corneal hysteresis a risk factor for ectasia?

- Corneal hysteresis is reduced after LASIK

Luce, JCRS, January 2005
Biomechanical Hypothesis Theory for Ectasia

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MORE RESEARCH IS NEEDED!

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The Cornea is a Viscoelastic Structure

- Corneal Response to RK
- Corneal Response to PRK
- Corneal Response to LASIK
- Corneal Response to INTACS
- Corneal Response to Cross-linking
- Ectasia: early or late?

Immediate Response

Time-Dependent Response

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Biomechanics: Safety and Efficacy

- Short-Term Corneal Response to Refractive Surgery
  - 2nd order response
  - Aberration Induction
  - Early ectasia

- Long-Term Corneal Response to Refractive Surgery
  - Drift in shape/vision
  - Late ectasia

- IOP Measurement (see Pepose at ASCRS)
The Most Significant New Development in terms of Corneal Biomechanics

The ability to Measure Biomechanical Properties in vivo

Before the development of wavefront sensors, few were interested in optical aberrations!

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Corneal Biomechanics can be exploited to manipulate corneal shape - and vision!

Biomechanical Customization
Can we achieve ........

the ideal corneal shape with

the ideal wavefront structure?

BIOMECHANICS!

Cynthia Roberts, Ph.D.
Thank You!
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