Corneal Deformation and Dynamics

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Relevance of Corneal Deformation

- **Diagnostics**
  - Keratoconus, pellucid marginal degeneration, etc.
  - Understanding the cause of poor BSCVA.

- **Refractive surgery**
  - Understanding how stress affects shape.
  - Minimizing ectasia complications.

- **Contact lens fitting**
  - Understanding & avoiding corneal warpage.
  - Enhancing orthokeratology outcomes.
Will we ever understand the etiology of ectasia?
Example of Corneal Warpage

Axial Diopters

SIM K's
43.24 D @ 84°
42.26 D @ 174°
Example of Corneal Warpage

Axial Diopters

SIM K's
44.15 D @ 82°
41.57 D @ 172°
Example of Orthokeratology

Paragon CVT lens

PRE

POST

Difference Map
Corneal Biomechanics

- Stress/strain relationship of collagen tissue.
- Hydration effects of ground substance.
- Structural organization and interaction of individual corneal components.
  - Anisotropy; non-homogeneity
- Cellular components.
  - Regulate hydration and effect repair.
- Controlling the boundary conditions.
  - Comparison of results.
Strain = $\xi = \Delta L/L$

Stress = $\sigma$
Stress in Various Forms

- Normal Stress (perpendicular to a surface)
  - Compression
  - Tension
- Shear Stress (parallel to a surface)
  - Linear
  - Rotational
- Hydrostatic Stress (omnidirectional)
Young’s modulus is the ratio of stress to strain:

\[ E = \frac{\sigma}{\xi} \]
Elasticity

Young’s modulus varies with different materials and composition.
Viscoelasticity

Young’s modulus varies with stress in nonlinear systems.
Viscoelasticity: Fast & Slow Components

- Piston Rod
- Piston and Seal
- Orifice / Restrictor

DASH POT
(energy dissipation element)

SPRING
(energy storage element)
Various combinations of serial and parallel springs and dashpots.
Hysteresis

The viscous component of a material causes a lag in the strain relaxation phase of the elastic response.
Plasticity

The ability to be permanently deformed or reshaped.

Typically caused by **damage** to the elastic component of a material.
Preconditioning

Cycling through an elastic response until a stable stress-strain function is achieved.

May involve displacement of water in the tissue or structural shifting.
Complication: Poisson’s Ratio

Transverse strain due to contraction.

Conservation of Volume or Biomechanical Coupling
In corneal tissue, the rule of conservation of volume (or surface area) can cause unbound water to be redistributed in the stroma.

This can affect the ability of the tissue to deform in a predictable manner.
Conservation of Surface Area

Axial Diopters

SIM K's
46.97 D @ 72°
43.79 D @ 162°
Arcuate Keratotomy (AK) incisions are used to reduce corneal astigmatism.

Flattening occurs at the incision and steepens the axis 90° away.
Material Properties of Collagen
Collagen Fibril Matrix (Lamellae)
Proteoglycans are soluble polymers with hydrophilic polysaccharide side chains (glycosaminoglycans) covalently linked to a core protein.
Corneal Lamellar Sheets
Histological View of Stroma
Biomechanical Testing of Cornea

Strip Extensiometry Method
Only a small proportion of the total collagen will bear the full tensile load.

Many collagen lamellae will be only partially loaded, if at all.

Young’s modulus can be underestimated.
Biomechanical Testing of Cornea

Whole globe testing

IOP
Normal Intact Human Cornea is Stable

Holographic Interferometry Method

Sclera

Cornea
Reichert Ocular Response Analyzer (ORA)

Notice that it is not a Corneal Response Analyzer!
Reichert ORA Measurement

Diagram showing the relationship between pressure and signal amplitude over time. Key features include:

- "In" Signal Peak
- "Out" Signal Peak
- Hysteresis
- Applanation Pressure 1
- Applanation Pressure 2

The graph illustrates the typical response of the ORA measurement system, with distinct peaks and the concept of hysteresis highlighted.
Figure 6 – Comparison of Corneal Hysteresis distribution of normal, keratoconic, and Fuchs’ subjects
Problems with ORA

- Doesn’t directly measure stress/strain.
- 20 msec response may be too short.
- Not a spatially resolved measurement.
  - Does not detect variations in material properties of the cornea in different locations or in depth.
- Lacks sensitivity.
- Lacks specificity.
- Measurement includes biomechanical response by the sclera and lamina cribosa.
Strain Imaging of Corneal Tissue With an Ultrasound Elasticity Microscope

Kyle W. Hollman, Ph.D., Stanislav Y. Emelianov, Ph.D., Jason H. Neiss, B.S., Gagik Jotyan, Ph.D., Gregory J.R. Spooner, Ph.D., Tibor Juhasz, Ph.D., Ron M. Kurtz, M.D., and Matthew O’Donnell, Ph.D.

FIG. 7. Average normal axial strain measured by ultrasound.
What Causes Corneal Shape?
Average Normal Corneal Shape

Average of 30 eyes
Does Structure Mediate Shape?
Interwoven Stromal Collagen Matrix
Pure Lamellar Structure Has Little Resistance to Shearing Stress
Depth-varying collagen act like trusses – the tensile stress is distributed to many layers.
Many Animals Lack Shear Resistance

- Limited shear resistance in the stroma
- Ink injection with corneal edema

Images obtained from the David Maurice historical website.

Hydration: 10 g H₂O/g dry weight

Shearing force
Important Differences in the Anterior and Posterior Stroma

Anterior interwoven half is barely distorted

Posterior lamellar half is easily distorted

Smolek MK. Interlamellar cohesive strength in the vertical meridian of human eye bank corneas. IOVS 1993; 34:2962-2969.
Interlamellar strength has similar profiles in fellow corneas. The patterns vary from person to person.
Corneal Collagen Cross-linking

- Riboflavin sulfate eyedrops (0.1%) applied topically.
- 365 nm UV light (3mW/cm²) is applied for about 30 minutes.
- New cross-links are believed to be established within and between fibrils.
Corneal Cross-linking

Before X-linking

After X-linking
Latest Cross-linking Method

- Uses sodium nitrite topical drops and no UV light.

- **Initial Studies Using Aliphatic β-Nitro Alcohols for Therapeutic Corneal Cross-linking.**
  - David C. Paik, Quan Wen, Richard E. Braunstein, Suzanna Airiani, and Stephen L. Trokel (*IOVS 2008 Pending*).

- **Short chain aliphatic beta-nitro alcohols for corneoscleral cross-linking: corneal endothelial toxicity studies.**
Spatially resolved biomechanical testing.
In vivo assessment of corneal structure.
Better knowledge of external forces.
- Eyelid tension, contact lens surface tension, etc.
Corneal cross-linking applications.
- What is it really doing?
- Can it be useful for inducing deformation?
- Will we be using cross-linking with contact lenses to change corneal shape?
To understand corneal deformation, you need to know:

- Viscoelasticity of the cornea.
- Biomechanical coupling.
- Inherent structural factors that mediate shape.
- Applied forces.
- Biomechanics of the entire eye.
- Boundary testing conditions.
Thank You.