# Multiphase Dynamics of Soft Biological Tissues


Sandia National Laboratories

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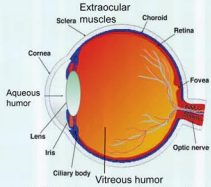
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Physical & Engineering Sciences

## Problem & Approach

**Problem :**
The characterization & predictive simulation of soft hydrated tissue is extremely complex nevertheless has numerous biomedical & biomimetic applications




http://webvision.med.utah.edu/anatomy.html

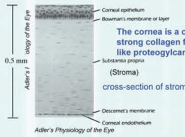
**Team :** B. Boyce (1824), M. Grazier (1824), T. Nguyen (8776), R. Jones (PI:8776)

**Approach :**
A closely integrated experimental & computational program, unique to Sandia, to evaluate the microstructural origins of cornea anisotropy & viscoelasticity

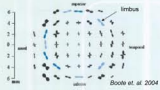
**Uniaxial tensile strip tests and constitutive modeling (FY05-FY06)**
- Creep & constant-rate tests to characterize nonlinear viscoelastic behavior.
- Guide development of anisotropic, viscoelastic constitutive model.
- Excised tissue. Requires preconditioning. Non-physiological response.
- Limited to central corneal region

**Pressurization tests and finite element modeling (FY06-FY07)**
- Intact tissue and physiological loading.
- Finite element model of pressurization experiments.
  - Guide refinement of anisotropic viscoelastic constitutive model.
  - Obtain physiological properties.

## Structural Anatomy of the Cornea

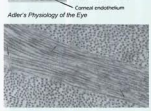



cross-section of stroma

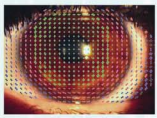



Boote et. al. 2004

polar plot of preferred fibril distribution for the cornea



cross-section of cornea showing interleaved lamellae

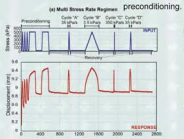


Aghamohammadzadeh et. al. 2004

## Results : Tensile Strip Tests

B.L. Boyce, R. E. Jones, T. D. Nguyen, "Stress-controlled viscoelastic tensile response of bovine cornea", Journal of Biomechanics, 2007.

-**Fresh, untreated tissue in saline bath** to best replicate *in vivo* properties
-**Stress control** to accommodate material remodeling after excision and preconditioning.

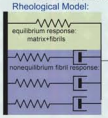




## Results: Non-linear anisotropic viscoelasticity model

T. D. Nguyen, B.L. Boyce, R. E. Jones, "A Nonlinear Viscoelastic Model for the Tensile Behavior of Bovine Cornea", submitted to Journal of Biomechanical Engineering

Rheological Model:




Free Energy Density:

$$W = W_m(I_1, I_4) + \frac{1}{2\pi}\int_{-\pi}^{\pi} W_1^{EQ}(\lambda(\theta))\,\phi(\theta,\mathbf{X})\,d\theta + \sum_k^N \frac{1}{2\pi}\int_{-\pi}^{\pi} W_k^{NEQ}(\lambda_k^t(\theta))\,\phi(\theta,\mathbf{X})\,d\theta$$

Fibril density function from x-ray scattering experiments

Flow rule (from dissipation inequality):

$$\frac{\dot{\lambda}_k^v}{\lambda_k^t} = \frac{1}{\eta_k(\tau_k)}\tilde{T}_k^{neq}$$

Multiplicative split:

$$\mathbf{F} = \mathbf{F}_e\mathbf{F}_v$$

Resolved stretches:

$$\lambda = \sqrt{\mathbf{C}:\mathbf{M}}$$

$$\lambda_k^t = \sqrt{\mathbf{C}_k^t:\mathbf{M}_k}$$

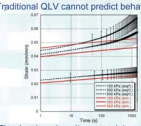
Nonlinear viscosity model with activation stress

$$\eta_k^{-1}(\tau_k) = \frac{\eta_0}{\eta_0\tau_k}\sinh\left(\frac{\tau_k}{\eta_0}\right)$$

reference viscosity; Activation stress

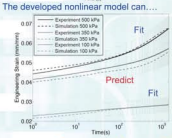
## Results: Uniaxial Creep & Rate Simulations

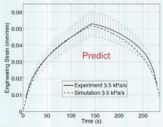
Traditional QLV cannot predict behavior



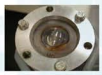

Novel, robust optimization procedure
- Fit elastic parameters to averaged stress-strain curve for high rate 350 kPa/s.
- Fit linear viscous parameters to 100 kPa creep by decades
- Fit nonlinear viscous parameters to 500 kPa creep
- Use parameters to predict cyclic tests and 350 kPa creep test.

The developed nonlinear model can....



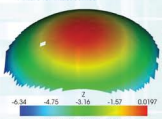




## Results : Intact Tissue Bulge Experiments

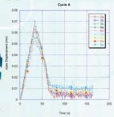


Fixture for intact cornea

Procedure:
- Intact cornea affixed by sclera & pressurized by saline solution on the anterior
- Digital image correlation (DIC) gives a full field displacement map of the surface
- Statistically relevant numbers of corneas are tested extract population trends




Full field displacement map



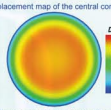

Apex displacement versus time shows repeatability across specimen population

DIC setup showing binocular cameras and back illumination of the cornea

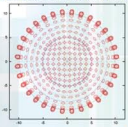
## Results : Bulge Simulations

- Needed to model complex geometry (directly from DIC) & fibril distributions (from X-ray scattering)
- Simulations show that :
  (a) the fibril distribution is optimized to maintain the shape of the central cornea, used in vision, during pressure excursions
  (b) despite the strong anisotropy in the central region, under pressure it behaves very close to isotropically

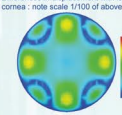
Displacement map of the central cornea




Fibril distribution map across cornea

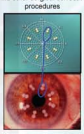


Differences in displacement with isotropic cornea : note scale 1/100 of above




## Significance

Laser Thermal Keratoplasty And other surgical corrective procedures



www.talleyeyecare.com/ltk.html

**This work can impact:**

Bio-mimetic composites

Soldier Suit

www.mit.edu/ian

Disease diagnosis & treatment, e.g. glaucoma

www.sandia.com

Ophthalmic Prosthetics and bio-compatibility

McLeod et al. 2003, Br. J. Ophthalmol

We are pursuing future funding
- Currently engaging Prof. Chris Wildsoet of UC Berkeley Vision Science Program in partnering for NIH/NEI funding on the role of the sclera in emmetropization and development of refractive errors (myopia and hyperopia).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