The eye

Sclera
OCULAR BIOMECHANICS

University of Pittsburgh

Sclera
Optic nerve
Optic nerve head (ONH)
Intraocular pressure
Vitreous humor
Retina
Lens
Cornea
Iris
Pupil
Intraocular pressure

To
Brain

www.BrainConnection.com
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ocural Biomechanics?

- Eye lids – Blinking and impact protection, closing and dry eye
- Cornea – Stable optics, lacerations, contact lenses, tonometry, transplants
- Iris/pupil – Dilation, floppy iris syndrome, surgery, pupillary or angle block
- Anterior chamber – Aqueous humor flow and outflow, intraocular pressure
- Ciliary processes – Aqueous humor formation
- Lens – Accommodation, artificial lenses, cataract formation
- Vitreous – Saccades, traction on the retina, drug delivery
- Retina – Detachment, tears, intravitreal gas bubbles, shaken baby syndrome
- Sclera – Myopia, glaucoma, optics, drug delivery, buckling
- Muscles – Eye movements, gaze
- Optic nerve head – Glaucoma, central retinal vein occlusion
- Optic nerve – Tumors, low or elevated cerebrospinal pressure
- Bruch’s membrane – Macular degeneration
- Vascular system – Adapt to changing conditions, perfusion pressure
- Impact mechanics – Paintballs, water jets, blast, splinters
EYELIDS

Blinking
Impact protection
Closing and dry eye
EYELIDS

Blinking
Impact protection
Closing and dry eye
CORNEA

Optics
Lacerations
Keratoconus
Contact lenses
Tonometry
Transport and hydration
Gonioscopy
Keratoplasty
Development
CORNEA

Optics
Lacerations
Keratoconus
Contact lenses

Tonometry
Transport and hydration
Gonioscopy
Keratoplasty
Development

Duane's Ophthalmology, Oculist.net
Corneal hysteresis and corneal resistance factor are two parameters that can be obtained using the Ocular Response Analyzer.

The meaning of these parameters, and their usefulness are, at best, questionable.
IOP CYRCDIAN RYTHM

Mosaed et.al., Am. J Ophthalmology, 139(2), 2005
CORNEA

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Lee and Zhuang, 2011
CORNEA

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Dr. Craig Boote's website
(http://www.projectsmagazine.eu.com/randd_projects/understanding_the_complexities_of_the_cornea)
CORNEA

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Development

ANTERIOR CHAMBER

Aqueous humor flow
Outflow
IOP

Amini and Barocas 2009
ANTERIOR CHAMBER

Aqueous humor flow

Outflow

IOP

Kagemann 2011
CORNEA

- Optics
- Lacerations
- Keratoconus
- Contact lenses
- Tonometry
- Transport and hydration

Gonioscopy

Keratoplasty

Amini and Barocas 2009
CORNEA

Optics
Lacerations
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Keratoplasty

\[ \Delta \theta = 8.2^\circ \]

\[ \Delta \theta = 24.5^\circ \]

\[ \Delta \theta = -6.7^\circ \]

\[ \Delta \theta = 12.5^\circ \]

\[ \Delta \theta = -9.7^\circ \]

\[ \Delta \theta = 6.7^\circ \]

\[ \Delta \theta = 3.5^\circ \]

Amini and Barocas 2009
IRIS / PUPIL

Dilation

Floppy iris syndrome

Cataract surgery

Iris interactions with the aqueous humor
LENS

Accommodation

Artificial lenses
LENS

Accommodation

Artificial lenses

Lanchares, Navarro and Calvo
Journal of Optometry, 5(3), 2012
VITREOUS

Saccades
Traction on the retina
Vitrectomy
Floaters
Drug delivery

Balachandran and Barocas 2011
VITREOUS

Saccades
Traction on the retina
Vitrectomy
Floaters
Drug delivery

Balachandran and Barocas 2011
RETINA

Detachment
Tears
Shaken baby syndrome
Intravitreal gas bubbles
Drusen

www.jdosmp.org
SCLERA

Optics
Myopia
Glaucoma
Drug delivery

**Buckling**
Penetrating injuries
Sclera indentation
Radiation treatments

www.retinaassociatesfla.com
MUSCLES

Eye movements
Gaze

www.pugcafe.com
MUSCLES

Eye movements

Gaze

Miller, Journal of vision, 7(11), 2007
OPTIC NERVE

Eye movements
Tumors
Cerebrospinal fluid
RETINA

Detachment
Tears
Shaken baby syndrome
Intravitreal gas bubbles
Drusen

The eye is viscoelastic!

The Heidelberg Retina Tomograph - HRT

Normal pressure
High pressure

Experimental Deformation

Simulated Deformation

Topography after 30 minutes at an IOP of 14.3 mmHg.
Change in topography 5 minutes after increasing IOP to 28.6 mmHg.
Difference in topography between waiting 5 minutes and 15 minutes at an IOP of 28.6 mmHg.

Sigal 2006
VASCULAR SYSTEM

Adapt to changing conditions
Perfusion pressure

Sugiyama et al. 1999
IMPACT MECHANICS

Paintballs
Water jets
Blast
Splinters
# IMPACT MECHANICS

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![Force vs Time Graph](Duane’s Ophthalmology, Oculist.net)

- Paintballs
- Water jets
- Blast
- Splinters
IMPACT MECHANICS

Paintballs
Water jets
Blast
Splinters

Duane’s Ophthalmology, Oculist.net
IMPACT MECHANICS

Paintballs
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Ocular biomechanics at the University of Pittsburgh

Modeling the optic nerve head to understand glaucoma
Glaucoma
Progressive loss of retinal ganglion cell axons causing irreversible loss of vision

Heidelberg Engineering
Elevated intraocular pressure is the main risk factor for the development of glaucoma.
Elevated intraocular pressure is the main risk factor for the development of glaucoma.

Why do some people develop glaucoma and some do not?

Perhaps due to differences in:
- Anatomy / Geometry
- Tissue composition → Mechanical properties
- Cellular responses or sensitivity

Frail eyes

Robust eyes
Outline

• Why study ONH biomechanics?
  • Modeling optic nerve head biomechanics
• What determines sensitivity to intraocular pressure?
• Biomechanics of progression
Strategy

Very tough to make measurements. (Surface measurements not as useful)

• Build models of the ONH.

• Simulate the ONH mechanical response to changes in intraocular pressure.

• Study the relationship between anatomy, mechanical properties and ONH response to IOP.
Generic model

Vary 21 factors

- 14 Geometry
- 6 Materials (5 modulus + 1 Poisson ratio)
- 1 Loading (Intraocular pressure)
Mean tensile strain in the pre-laminar neural tissue is highly influential. Sigal et al., IOVS, Nov 2005.
Why Does the Sclera Matter?

Total deformation at 50 mmHg IOP

Deformation exaggerated 6 times, with corneal apex fixed
Myopes put Greater Shear Stress on LC
Higher Risk for Glaucomatous Changes

Stress on any part of ocular shell related to IOP and radius of structure: 
\[ \sigma = \frac{PR}{2t} \]
\( \sigma \) = circumferential stress
P = IOP
R = radius of curvature at that part of the globe
T = thickness
Thus, in myopic eyes when LC is cupped, radius is larger, and stress is greater

From Christian Otto's NASA's Informational Briefing:
Risk of Microgravity-induced VIIP
Individual-specific models from histology

Sigal et al., Technology and Health Care, Aug 2005
My area of ocular biomechanics

Direct imaging of optic nerve head biomechanics
In-vivo ONH biomechanics

Normal pressure

Elevated Pressure
In-vivo ONH biomechanics
In-vivo ONH biomechanics
In-vivo ONH biomechanics
In-vivo ONH biomechanics
My area of ocular biomechanics

VIIP
OPTIC NERVE HEAD

VIIP
Glaucoma
Central retinal vein occlusion
Mader et.al., Ophthalmology, 118(10), 2011
OPTIC NERVE HEAD

Mader et al., Ophthalmology, 118(10), 2011
OPTIC NERVE HEAD

From Christian Otto's NASA's Informational Briefing: Risk of Microgravity-induced VIIP
Christian Otto’s adaptation of Rekate 2008 Cerebrospinal Fluid Research
OPTIC NERVE HEAD

Dr. Story Musgrave conducting tonometry on STS 44

From Christian Otto’s NASA's Informational Briefing:
Risk of Microgravity-induced VIIP
Aerobic exercise may be protective as it draws cephalad fluid caudally into lower limbs

Strength training may cause potentially damaging transient spikes in ICP

From Christian Otto’s NASA’s Informational Briefing: Risk of Microgravity-induced VIIP
My area of ocular biomechanics

Fibrous architecture of the eyes
The eye
The ONH
And why is this important?

Fibers act very differently depending on their orientation.

- Strong when pulled
- Soft when pushed
- Soft when bent
And why is this important?

Fibers act very differently depending on their orientation

- Strong when pulled
- Soft when pushed
- Soft when bent
And why is this important?

Fibers act very differently depending on their crimping.
And why is this important?

Muscle insertion
Ocular biomechanics

The examples shown span wide ranges of:

– Spatial scale (whole body vs. organ vs. cell)
– Temporal scale (fast vs. slow)
– Models, theory and experiments
– Well established vs. cutting edge
– Solid, fluid and gas mechanics
– Applied science vs. basic science
– Naturally evolved vs. designed
Examples of ocular biomechanics

• Optics
• Fluid mechanics
• Solid mechanics
• Growth and remodeling
• Thermodynamics
• Mechanotransduction
Some key ocular properties

Soft tissue:
- Thickness and anatomic distribution
- Stiffness and non-linearity
- Inhomogeneity
- Anisotropy
- Viscoelasticity
- Strength and robustness

Fluid (liquid and gas):
- Pressure
- Volume
- Viscosity
- Velocity
- Vorticity
- Surface tension

Other properties:
- Optical properties
- Thermal properties
- Radiation absorption
- Chemical stability
- Ability to remodel
www.ocularbiomechanics.org

Ian A. Sigal, PhD