Biomechanics of the Optic Nerve Sheath in VIIP Syndrome

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Visual Impairment and Intracranial Pressure (VIIP) Syndrome

- Permanent changes in visual function after long-duration space flights
  - 41.7% incidence in U.S. astronauts
Structural Changes in the Optic Nerve

Cephalad Fluid Shifts

1G
- 70 mmHg
- 100 mmHg

Cerebral Venous Congestion

0G
- 100 mmHg

Facial puffiness
- 100 mmHg

Loss of Hydrostatic Drainage

Bird-legs

200 mmHg

100 mmHg

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Hypothesis

Increased CSF pressure drives remodeling of the posterior eye and the optic nerve sheath
Goal

Study the biomechanical response of the optic nerve sheath and posterior eye to elevated CSF pressures

- Eventually, understand visual disturbances that occur during long-duration space travel
Optic Nerve Sheath: Anatomy


EXPERIMENTS
Experimental Protocol: Inflation Test

1. Sheath is peeled away from the nerve proper

2. Nerve proper is cut away

3. The optic nerve sheath is cannulated and connected to a pressure control system
System Components:
1 - Specimen bath/mounted porcine eye
2 - Syringe pump
3 - Pressure transducers
4 - CCD camera
Pressure-Diameter Tests
Modulus Increases at Higher Pressures

\[ \varepsilon = \frac{r}{r_o} - 1 \quad \sigma = \frac{Pr}{h} \]

Mean ± SEM
n=7

Pressure (mm Hg)
Permeability - Experimental Setup
### Permeability - Results

<table>
<thead>
<tr>
<th>Permeability</th>
<th>(μL/min/cm²/mm Hg)</th>
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<td>0.79 ± 0.12</td>
<td>(mean ± SEM; n=17)</td>
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**Implication for Humans:**

Outflow Rate = \( K \cdot P \cdot A = 125 \frac{\text{mL}}{\text{day}} \) at 7 mm Hg

20% of daily CSF production

\[ A = 2 \cdot (\pi DL) \]

[Image: Geeraerts et al. Critical Care, 2008.]
Collagen Structure

Post Mortem Porcine Optic Nerve Sheath

Arterial Adventitia
Collagen Orientation Changes with Pressure

0 mm Hg

30 mm Hg

100 μm

100 μm

Axial

Circ
Experimental Summary

• Optic nerve sheath exhibits typical soft tissue behavior:
  – Preconditioning effect, with repeatable behavior after 4\textsuperscript{th} pressure cycle
  – Nonlinear stiffening
  – Anisotropic collagen orientation

• Structure and behavior appears to be similar to the adventitia

• High permeability suggests CSF drainage could play an important role in fluid transport in the optic nerve sheath
Limitations

• Peeling back the meninges could cause structural damage

• Lack of availability of long human optic nerves

• Post mortem effects on permeability?
MODELING
Basic Modeled Geometry


Adopted from Ekington et al. 1990
Two dura mater geometries considered

**Model 1:**
Dura expanded in bulbar segment

**Model 2:**
Dura tighter in bulbar segment
Optic Nerve Head (ONH) Geometry

- Based on models of Sigal et al., 2005
Material parameters

- Linearly elastic
  - Sclera – 3.0 MPa
  - Peripapillary Sclera – 3.0 MPa
  - Lamina Cribrosa – 0.3 MPa
  - Pia Mater – 3.0 MPa
  - Dura Mater – 1.0 MPa
  - Retinal Vessel Wall – 0.3 MPa
1. Baseline (Standing or walking)
   IOP - 15 mmHg   ICP - 0 mmHg   RVP - 55 mmHg

2. Supine
   IOP - 15 mmHg   ICP - 12 mmHg   RVP - 55 mmHg

3. Elevated ICP
   IOP - 15 mmHg   ICP - 30 mmHg   RVP - 55 mmHg
von Mises Stress

Baseline
Supine
Elevated ICP

Expanded Dura

Tighter Dura

0.05 MPa

0.0
von Mises Stress Distributions

Expanded Dura

Tighter Dura

von Mises Stress (MPa)
Y-displacement

ICP = 0 mmHg

ICP = 30 mmHg

Scale:

0.4 mm

0.002 mm

-0.01 mm
Z-displacement

ICP = 0 mmHg

ICP = 30 mmHg

Scale:

-0.01 mm

-0.04 mm
1\textsuperscript{st} Principal Strain

ICP = 0 mmHg

ICP = 30 mmHg

Scale:

0.06

0.0
2nd Principal Strain

Baseline

Elevated ICP

Scale:

0.03

0.4 mm

0.0
Increase ICP: 0 to 30 mmHg

* Color scale is total displacement
Regions of Interest

Lamina Cribrosa

Optic Nerve 1 mm
Principal Strain Distributions

Lamina Cribrosa

1st Principal Strain

2nd Principal Strain

3rd Principal Strain

Optic Nerve

ICP

- 0 mmHg
- 12 mmHg
- 30 mmHg
Future Directions

- Quantify collagen microstructural changes during mechanical loading
- Incorporate collagen microstructure into computational models of VIIP syndrome
- Study possible static instability in ONS
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Key dates:  
• January 16, 2015: abstract submission deadline  
• Mid-April, 2015: early bird registration  
• June 17-20, 2015: SB^3C Meeting at Snowbird, Utah

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