Optic Nerve Sheath Mechanics and Permeability in VIIP Syndrome

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Visual Impairment and Intracranial Pressure Syndrome (VIIP)

- Altered visual function following long-duration space flights
- 41.7% incidence in the U.S.
- Physiological adaptations to microgravity
- Cephalad fluid shifts
Cephalad Fluid Shifts

1G

70 mmHg

100 mmHg

Cerebral Venous Congestion

Loss of Hydrostatic Drainage

9.8 m/s²

0G

100 mmHg

100 mmHg

Facial puffiness

Bird-legs

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Structural Changes in the Optic Nerve

Tortuous optic nerve observed in an astronaut with visual disturbances following long duration space flight. Taken from Kramer et al. Radiology, 2012.
• Goal: study the mechanical properties of the optic nerve sheath at various CSF pressures to understand visual disturbances that occur during long-term space travel

• Hypothesis: increased CSF pressure drives remodeling of the posterior eye and the optic nerve sheath
Optic Nerve: Anatomy

Cross Section


Low Pressure

High Pressure

Dura

Pia

Nerve Proper

Experimental Protocol

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
Experimental 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

\[ \varepsilon = \frac{r}{r_o} - 1 \quad \sigma = \frac{Pr}{h} \]
Collagen Fiber Orientation
Collagen Orientation Changes with Distance from the Globe
Collagen Fiber Undulation
Collagen Fiber Undulation

% Engagement = \frac{T}{C} \cdot 100

Collagen Structure

Optic Nerve Sheath

Arterial Adventitia

Blood Vessel Behavior

- Remodel in response to high pressures
- Wall thickens to reduce stress on cells
  \[ \sigma = \frac{Pr}{h} \]
- Appear to remodel towards target stresses
Permeability-Experimental Setup
Permeability-Results

\[ K = \frac{V}{P \cdot A \cdot t} \]

V: outflow volume (\(\mu\)L)
P: pressure (mm Hg)
A: optic nerve surface area (cm\(^2\))
t: time (s)

Permeability
(\(\mu\)L/min/cm\(^2\)/mm Hg)

0.79\(\pm\)0.12 (n=17)

Estimation for Humans:

Outflow Rate = \(K \cdot P \cdot A = 125 \frac{mL}{day}\) at 7 mm Hg
20% of daily CSF production

Summary

• Optic nerve sheath exhibits typical soft tissue behavior:
  – Preconditioning effect in the early cycles of cyclic pressure
diameter testing
  – Repeatable behavior following the fourth pressure-
diameter cycle
  – Nonlinear stiffening at pressures
  – Anistropic behavior due to collagen orientation

• Structure and behavior appears to be similar to the
adventitia

• High permeability suggests CSF drainage could play an
important role in VIIP syndrome
Limitations

• Peeling away the meninges could cause structural damage

• Lack of availability of long human optic nerves

• Post mortem effects on permeability
Future Directions

• Quantify microstructural changes during mechanical loading

• Incorporate results into computational models of VIIP syndrome
  – Help identify possible interventions
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