# Biomechanics of the Optic Nerve Sheath in VIIP Syndrome

C. Ross Ethier[1], Julia Raykin[1], Rudy Gleason[1], Lealem Mulugeta[3], Jerry Myers[2], Emily Nelson[2], Brian C. Samuels[4]

[1]Department of Biomedical Engineering, Georgia Institute of Technology/Emory University, Atlanta, GA; [2]NASA Glenn Research Center, Cleveland, OH; [3]Universities Space Research Association, Houston, TX; [4]Department of Ophthalmology, U. Alabama at Birmingham, Birmingham, AL

Georgia Tech

Wallace H. Coulter Department of Biomedical Engineering at Georgia Tech and Emory University

EMORY UNIVERSITY

# Disclosures and Acknowledgements

Disclosure: None

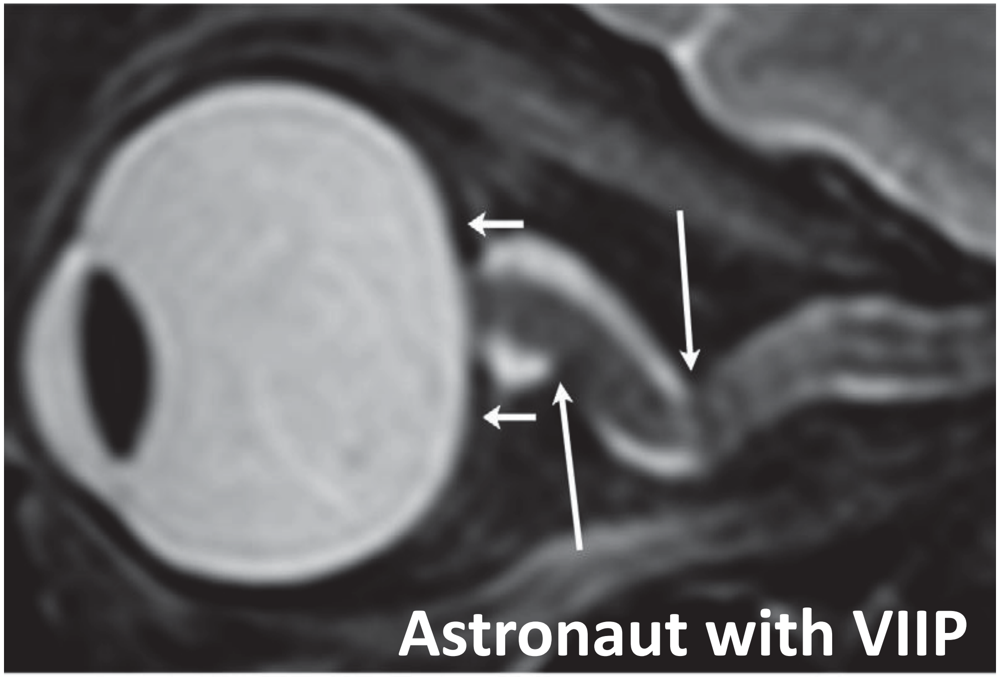
Funding

- NASA (CRE)
- Georgia Research Alliance (CRE)

# Visual Impairment and Intracranial Pressure (VIIP) Syndrome

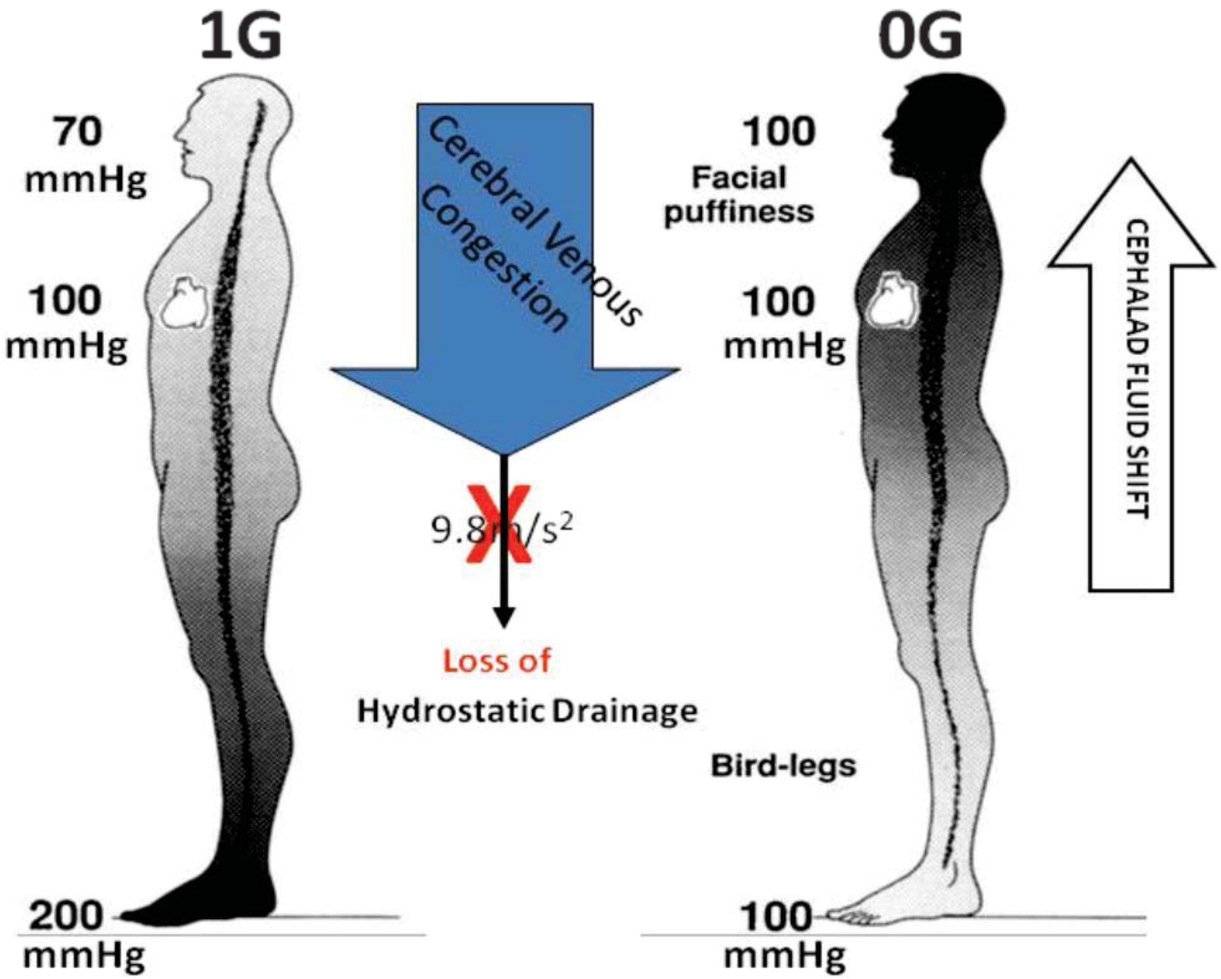
- Permanent changes in visual function after long-duration space flights
  - 41.7% incidence in U.S. astronauts

# Structural Changes in the Optic Nerve


Kramer et al. Radiology, 2012.

# Cephalad Fluid Shifts




humanresearchroadmap.nasa.gov

# Hypothesis

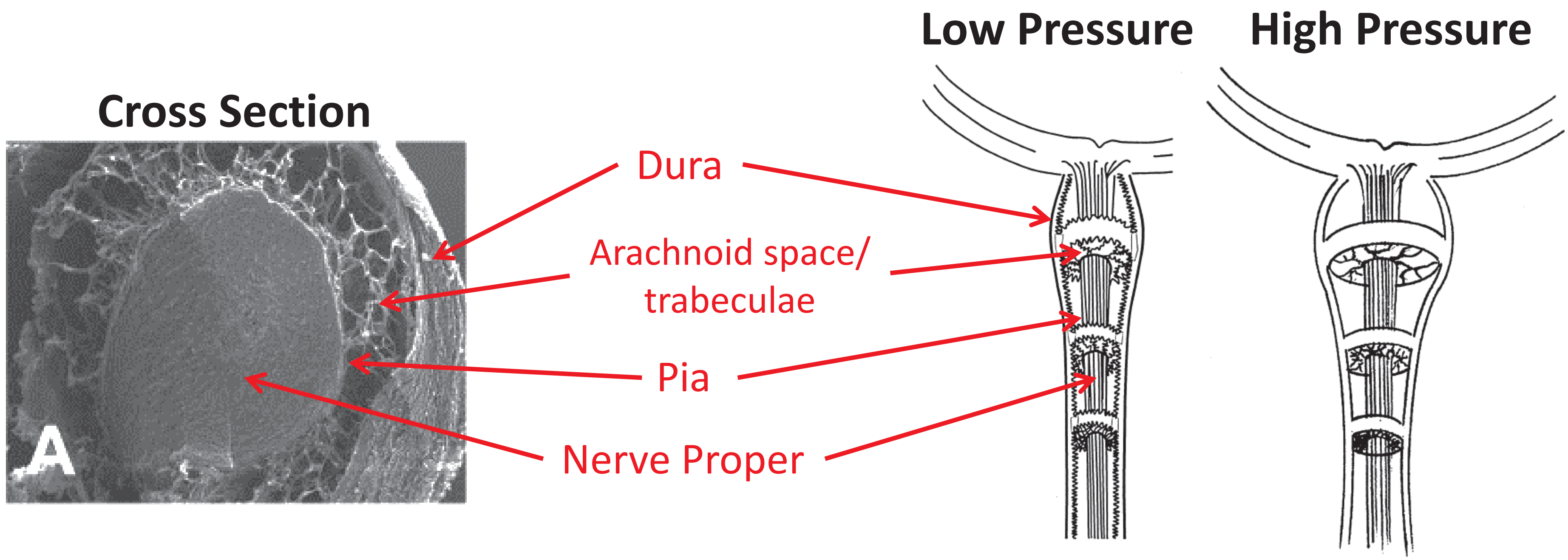
Increased CSF pressure drives remodeling of the posterior eye and the optic nerve sheath

# 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

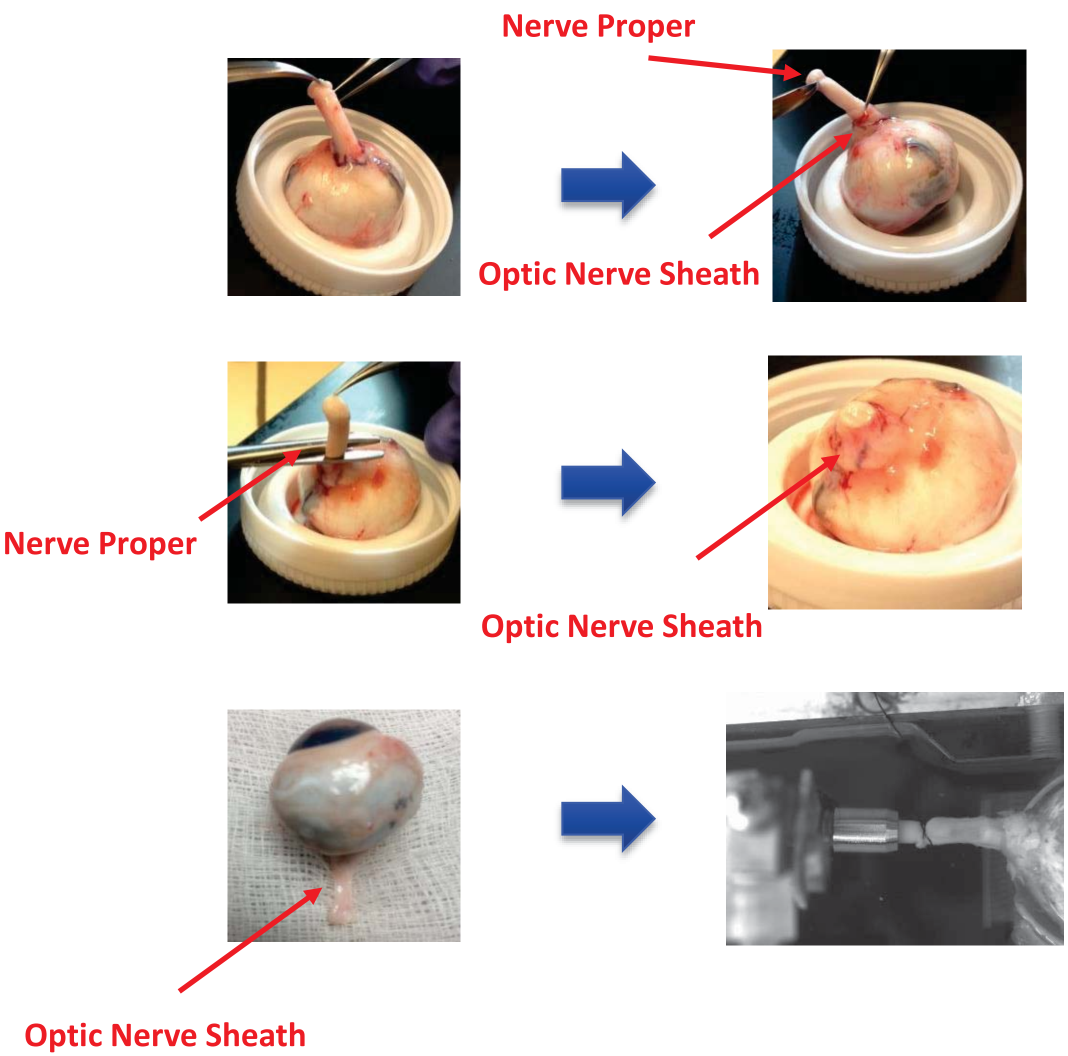



Killer et al. Brain, 2006.

Hansen et al. Acta Ophthalmologica, 2011.

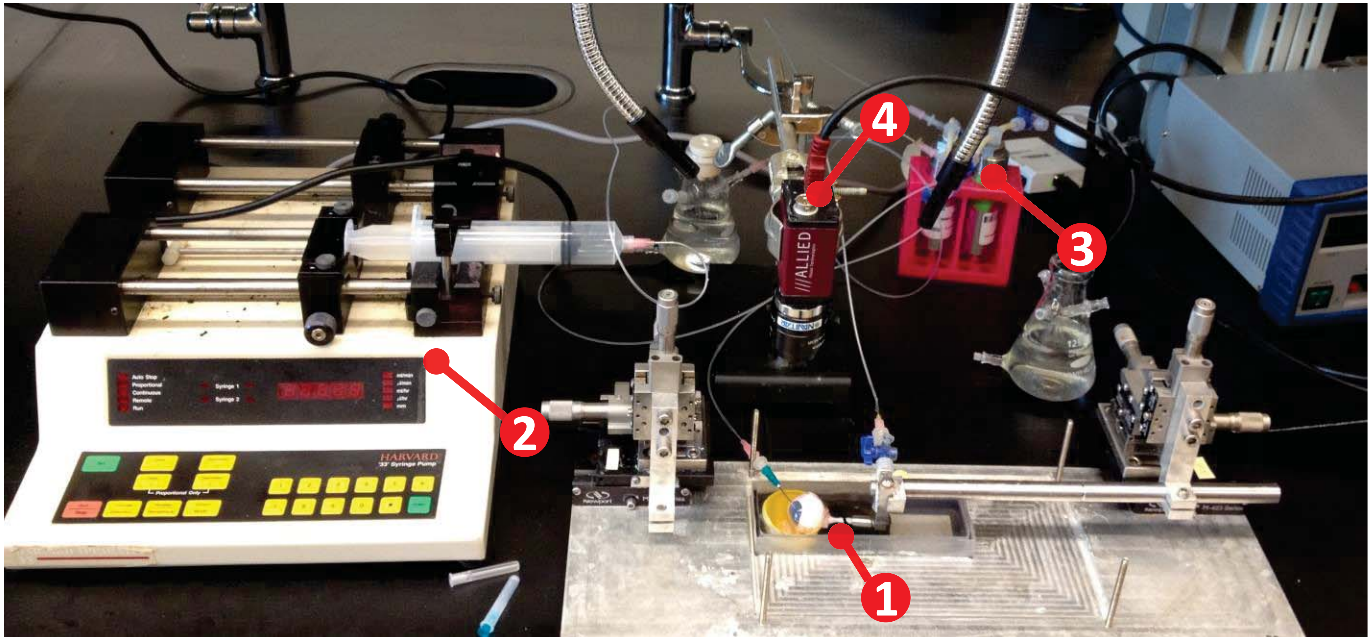
# EXPERIMENTS

# 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

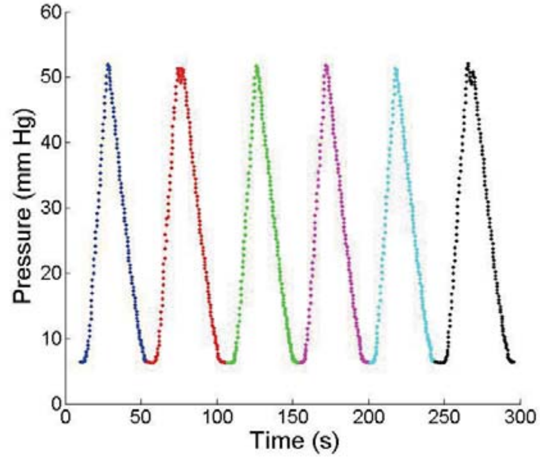
# Experimental System

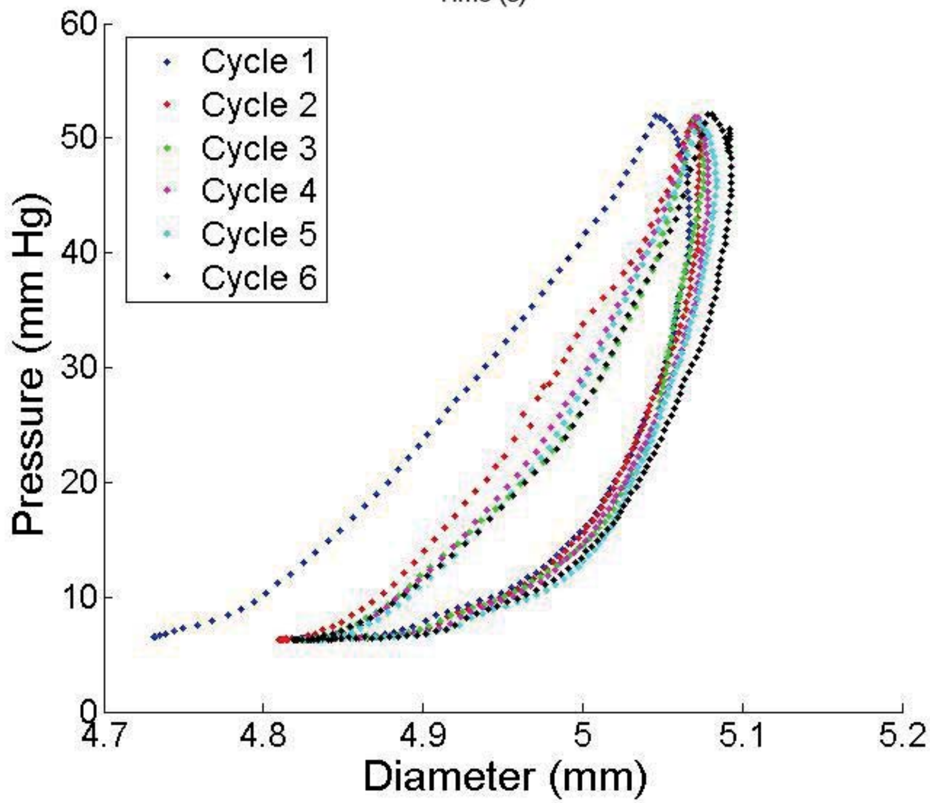



***System Components***:

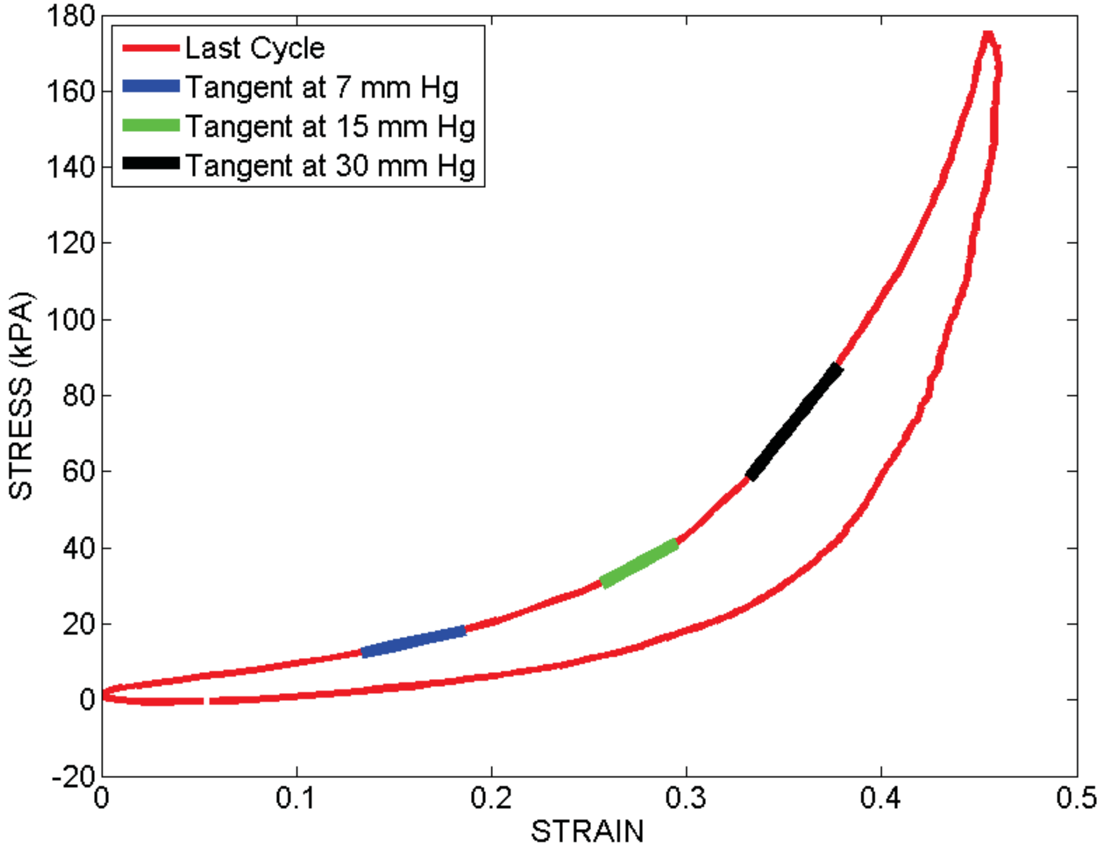
**1** - Specimen bath/mounted porcine eye
**2** - Syringe pump
**3** - Pressure transducers
**4** - CCD camera

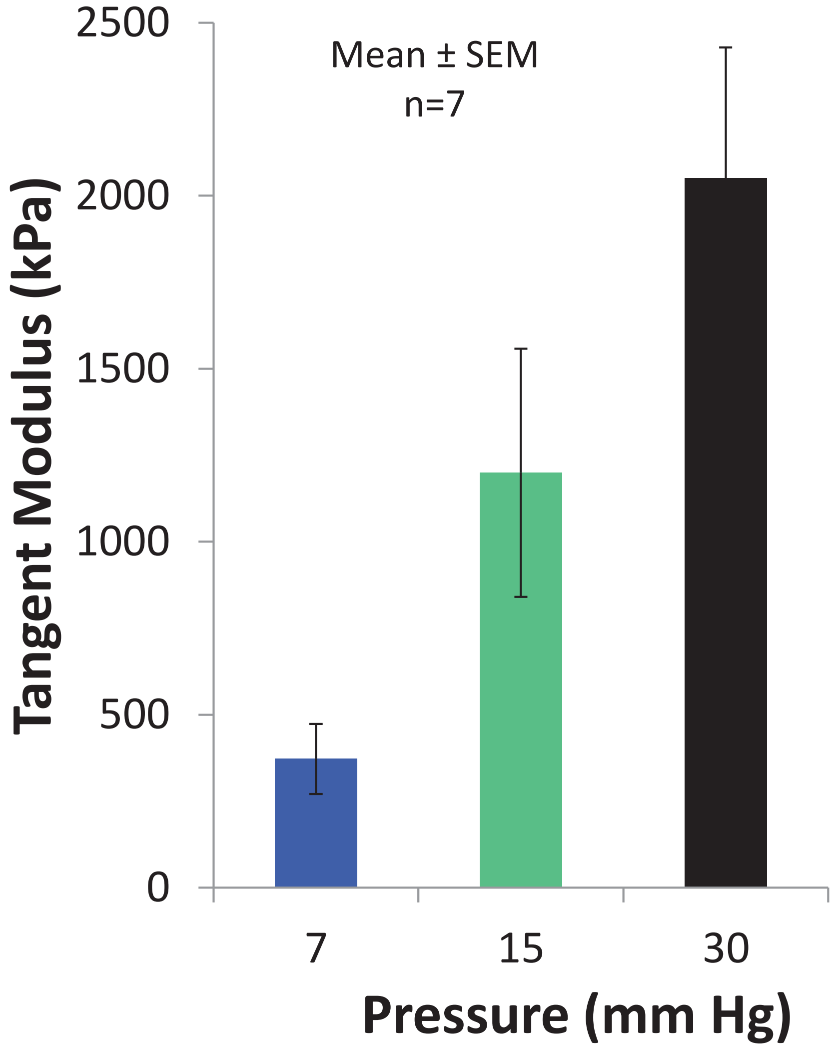
# Pressure-Diameter Tests



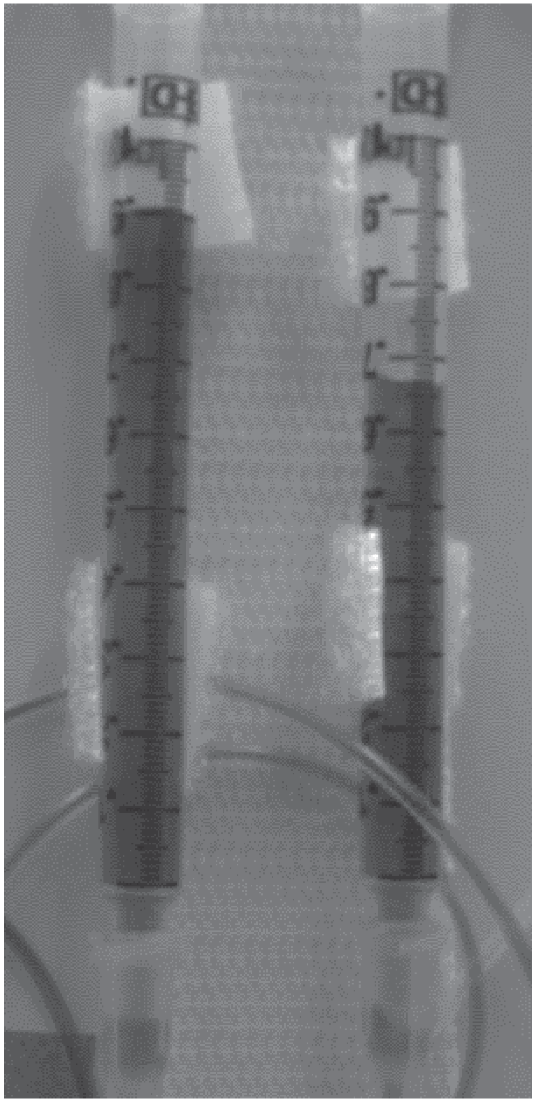

# Modulus Increases at Higher Pressures

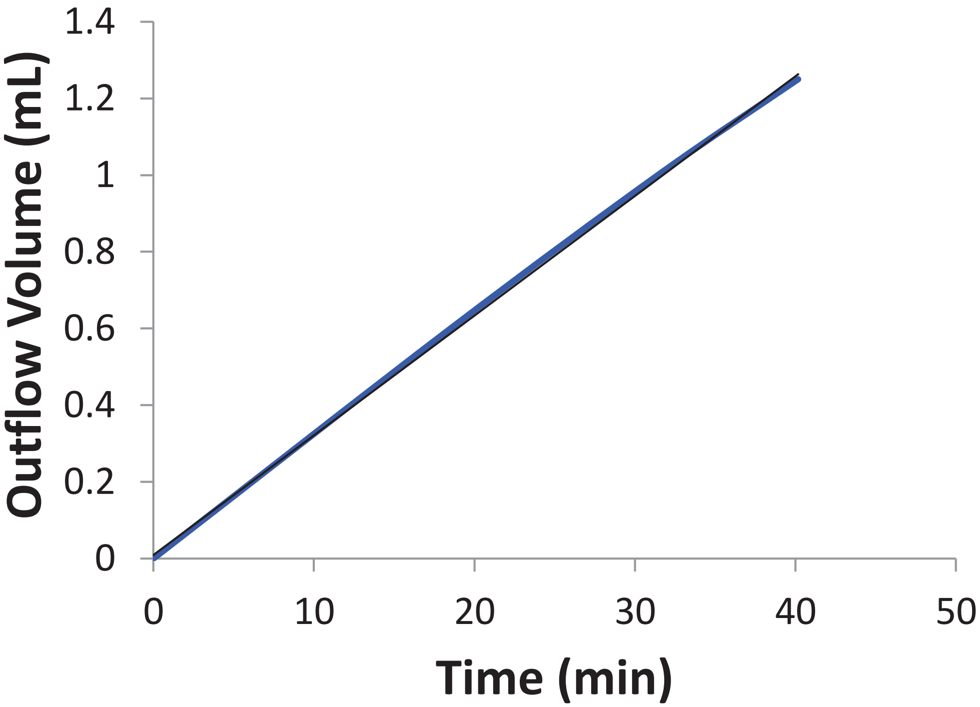



$$\varepsilon = \frac{r}{r_o} - 1 \qquad \sigma = \frac{Pr}{h}$$

# Permeability - Experimental Setup

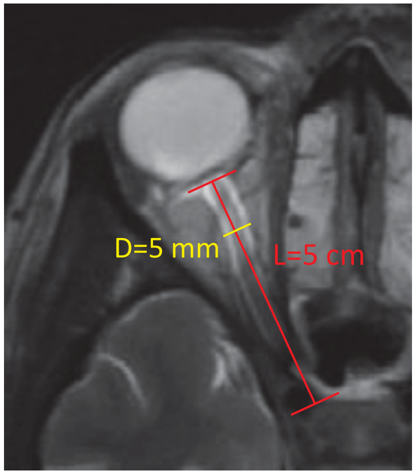




# Permeability - Results

| Permeability ($\mu L/min/cm^2/mm\ Hg$) |
| --- |
| 0.79 ± 0.12 (mean ± SEM; n=17) |

$$A = 2 \cdot (\pi D L\,)$$



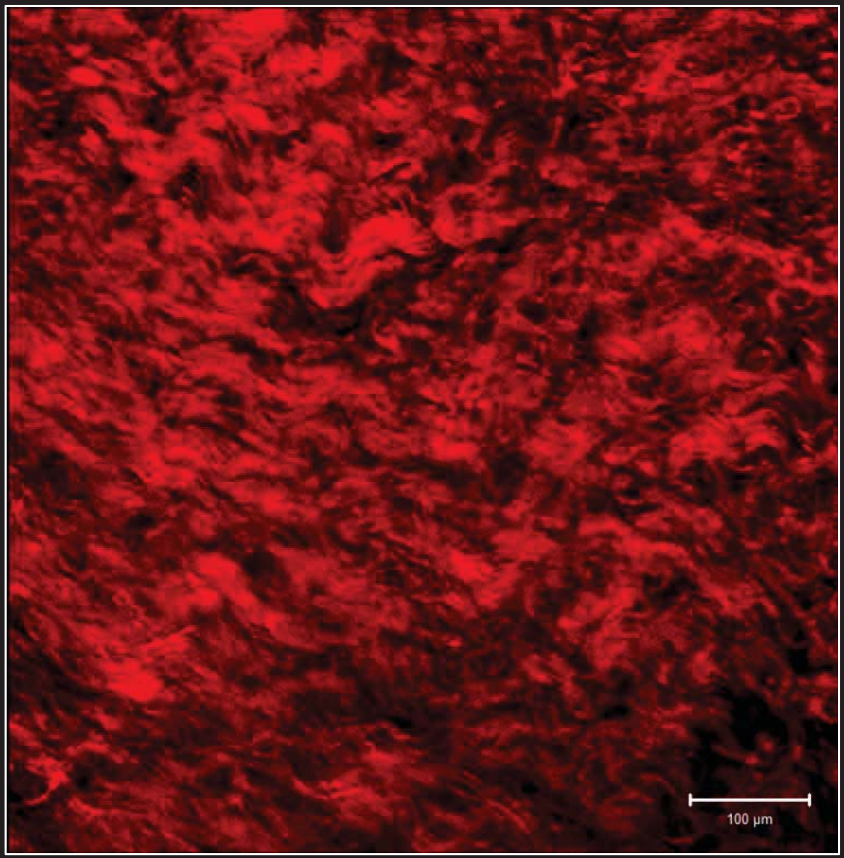
Geeraerts et al. Critical Care, 2008.

## Implication for Humans:

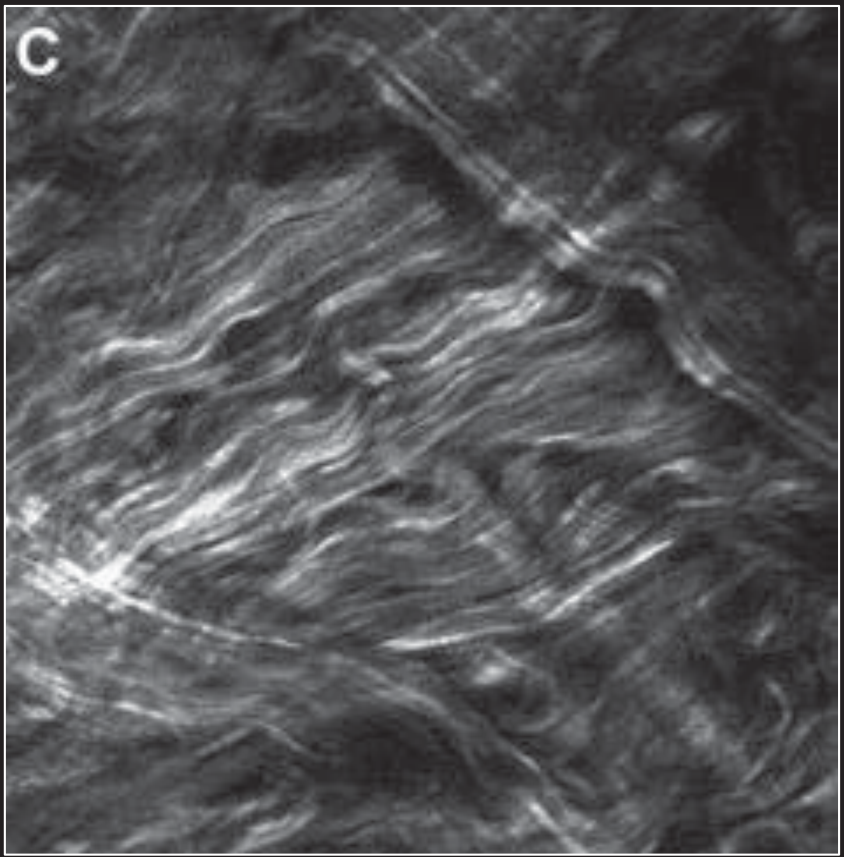
$Outflow\ Rate = K \cdot P \cdot A = 125\,\frac{mL}{day}$ at 7 mm Hg

20% of daily CSF production

# Collagen Structure



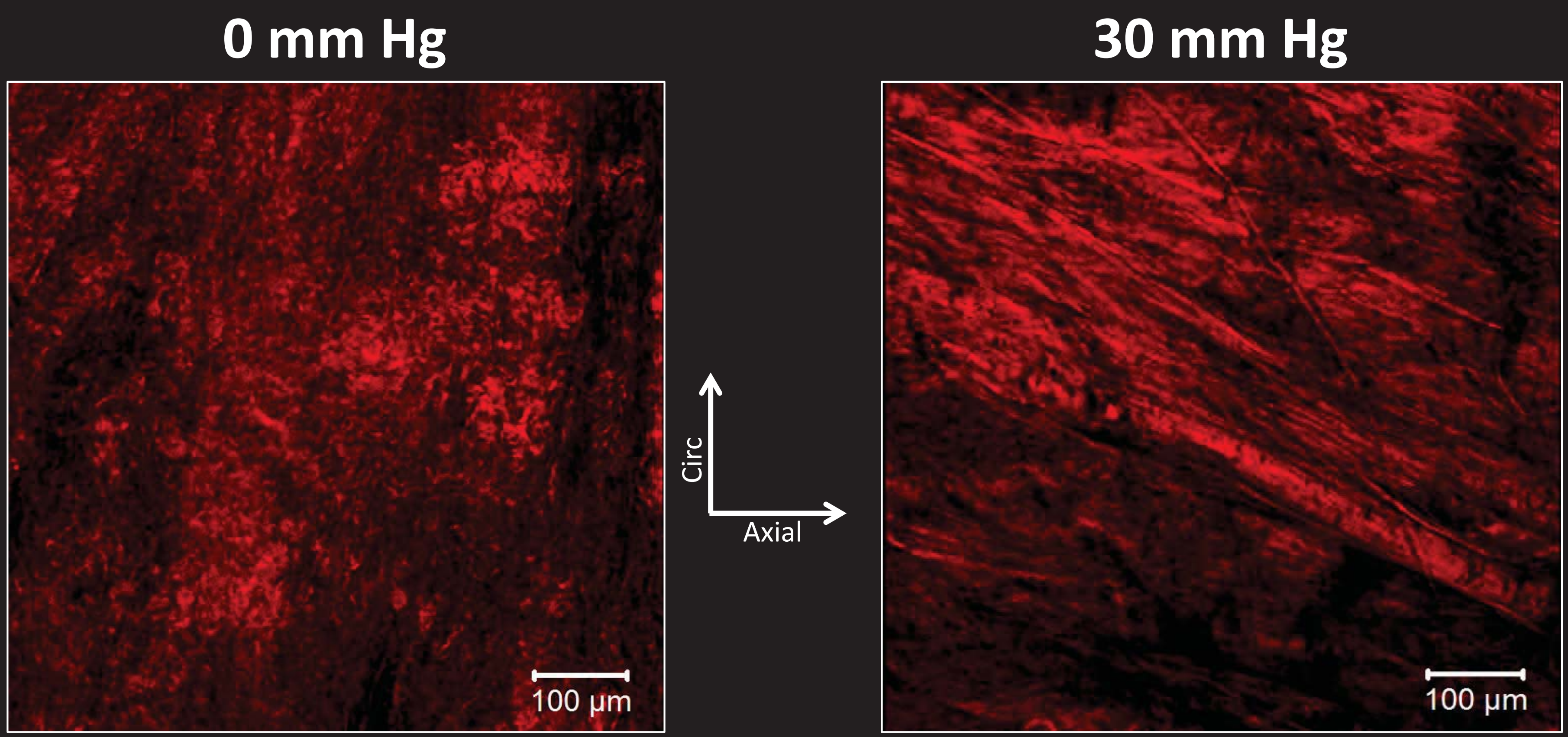

Post Mortem Porcine Optic
Nerve Sheath




Arterial Adventitia

Beal et al. Journal of Surgical Research, 2013.

# Collagen Orientation Changes with Pressure



# Experimental Summary

- Optic nerve sheath exhibits typical soft tissue behavior:
  - Preconditioning effect, with repeatable behavior after $4^{th}$ pressure cycle
  - Nonlinear stiffening
  - Anisotropic collagen orientation

- Structure and behavior appears to be similar to the adventitia

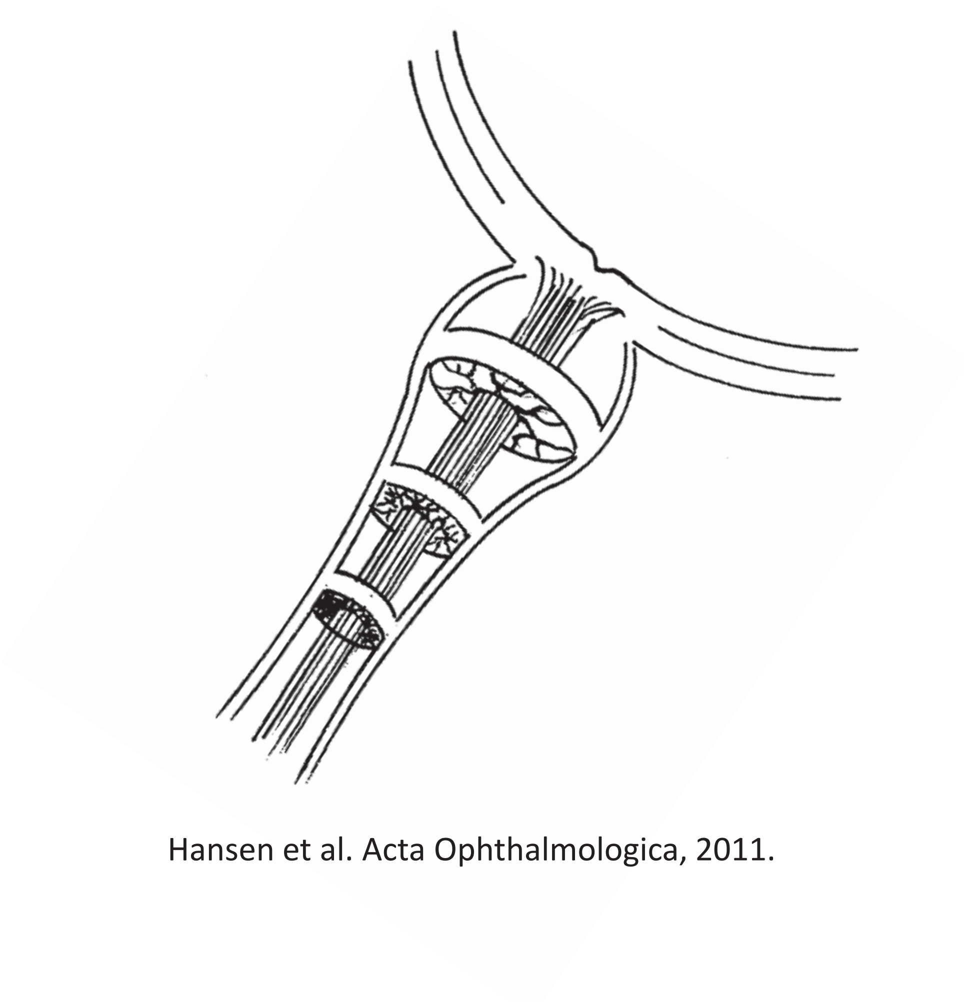
- High permeability suggests CSF drainage could play an important role in fluid transport in the optic nerve sheath

# Limitations

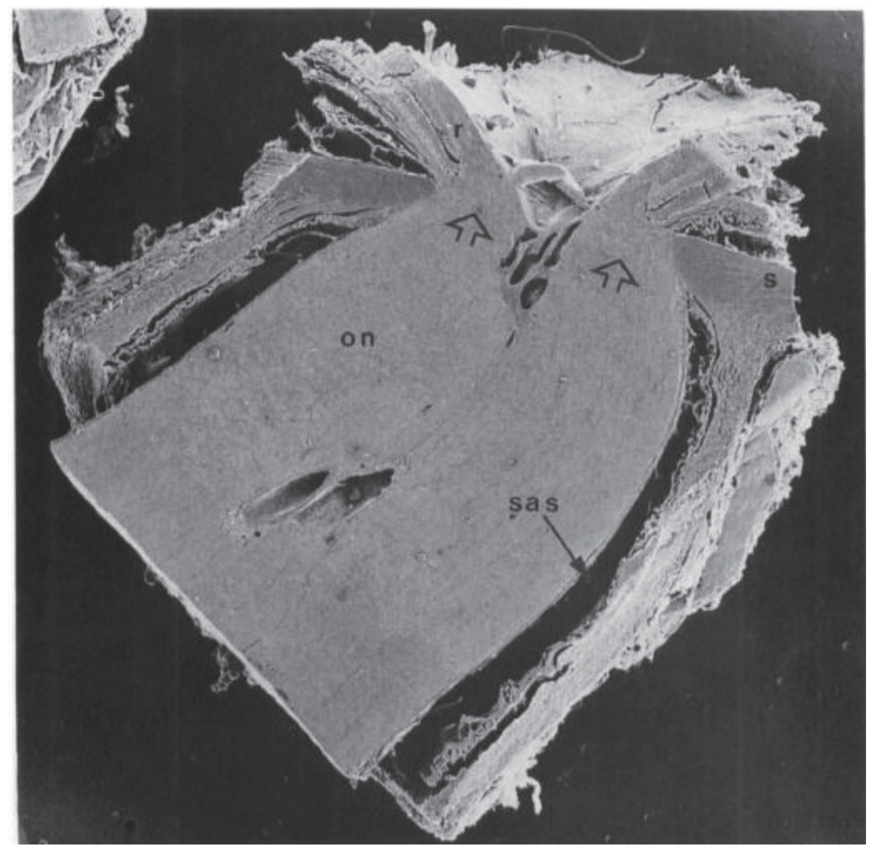
- Peeling back the meninges could cause structural damage
- Lack of availability of long human optic nerves
- Post mortem effects on permeability?

# MODELING

# Basic Modeled Geometry



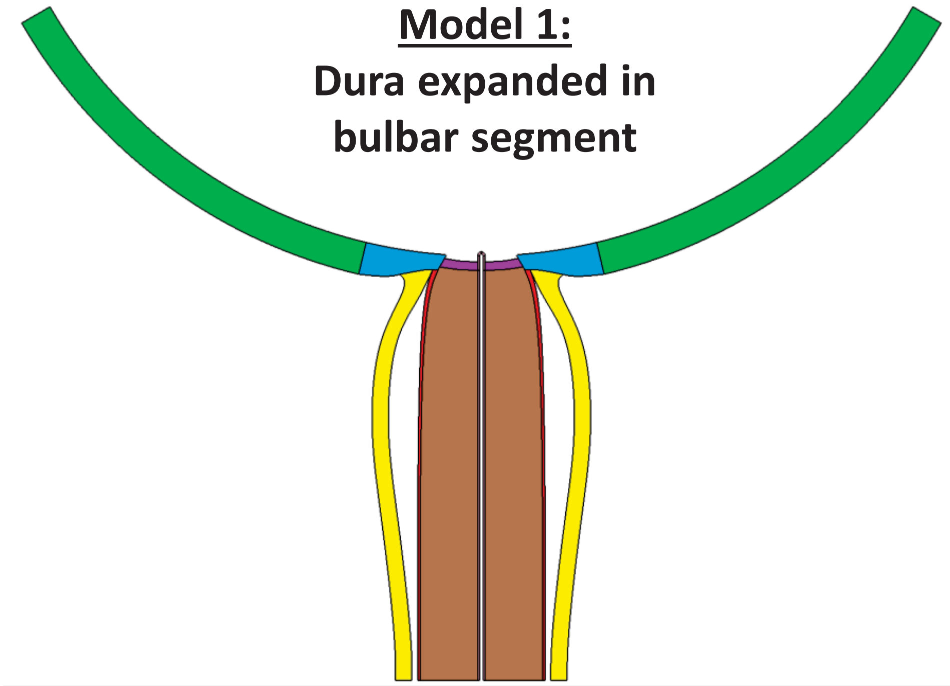
Hansen et al. Acta Ophthalmologica, 2011.

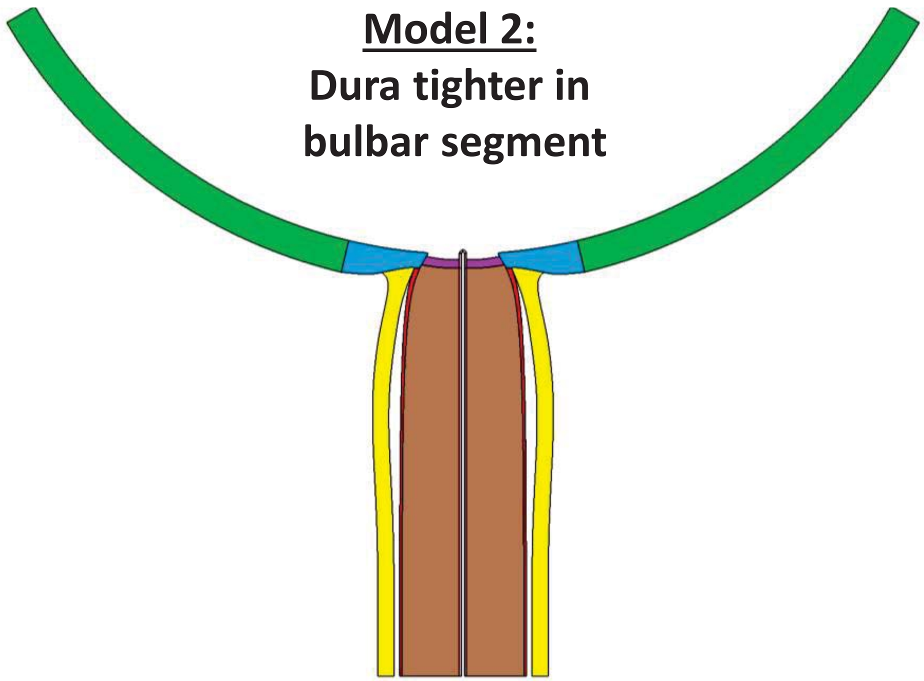



Adopted from Ekington et al. 1990

# Basic Modeled Geometry

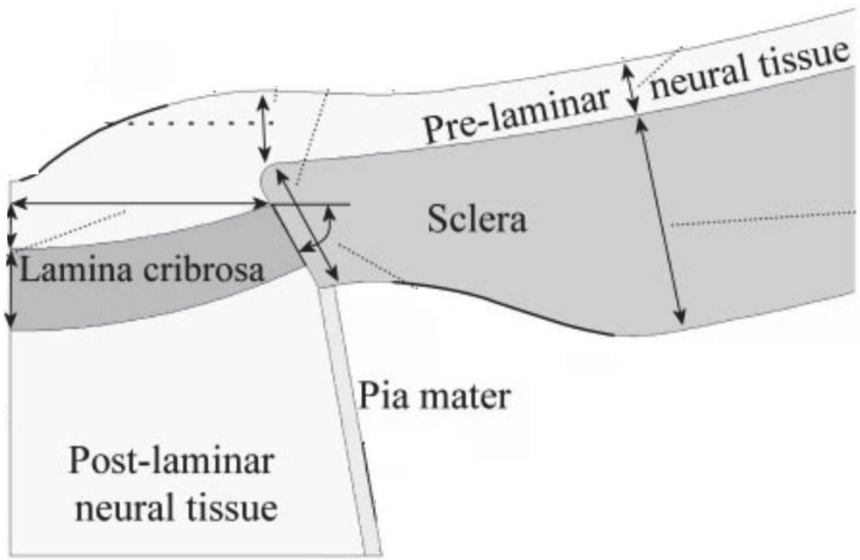
Two dura mater geometries considered



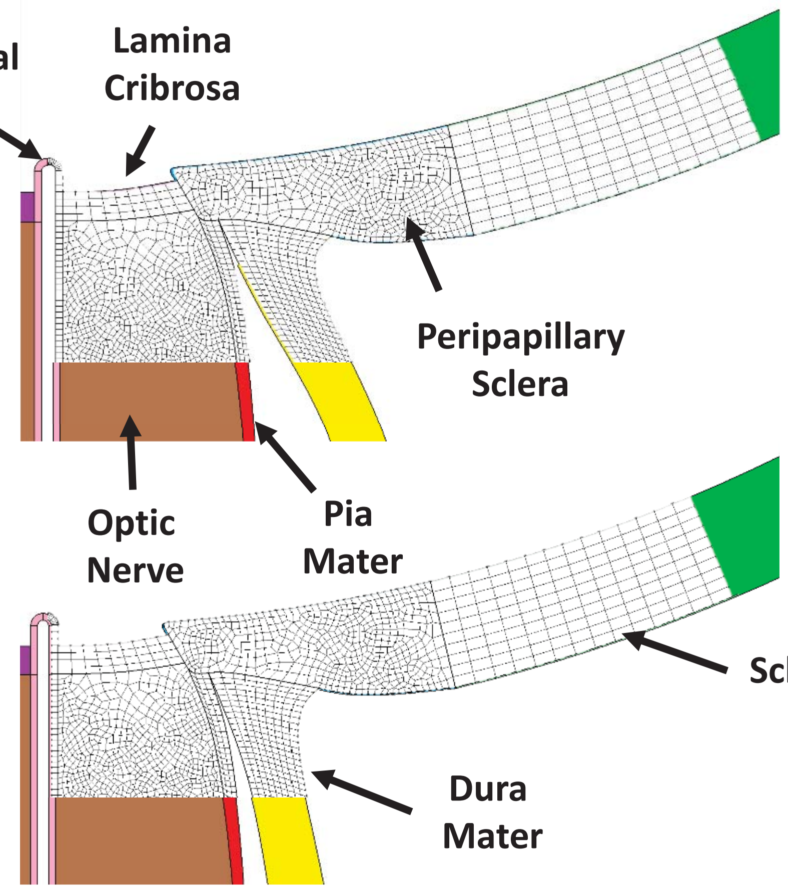



# Optic Nerve Head (ONH) Geometry

- Based on models of Sigal et al., 2005

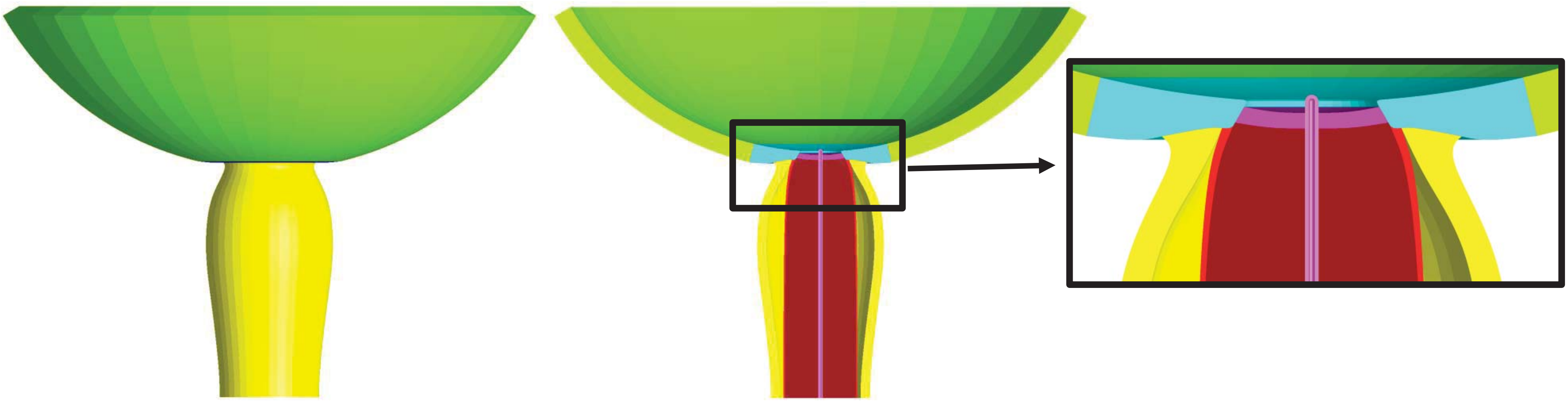



Sigal et al. 2005



# 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



# Loading

1. Baseline (Standing or walking)

   IOP – 15 mmHg **ICP - 0 mmHg** RVP – 55 mmHg

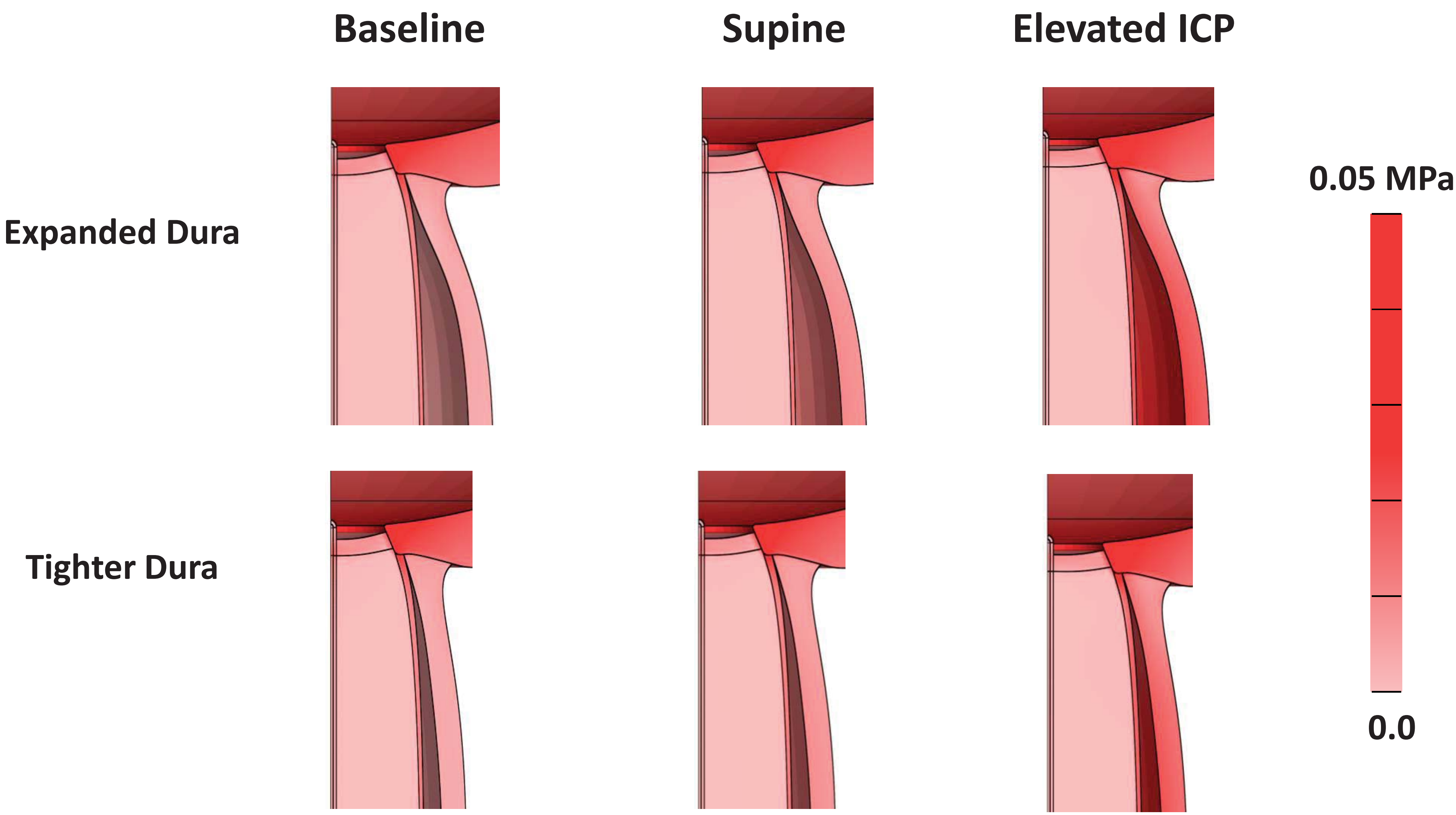
2. Supine

   IOP – 15 mmHg **ICP - 12 mmHg** RVP – 55 mmHg

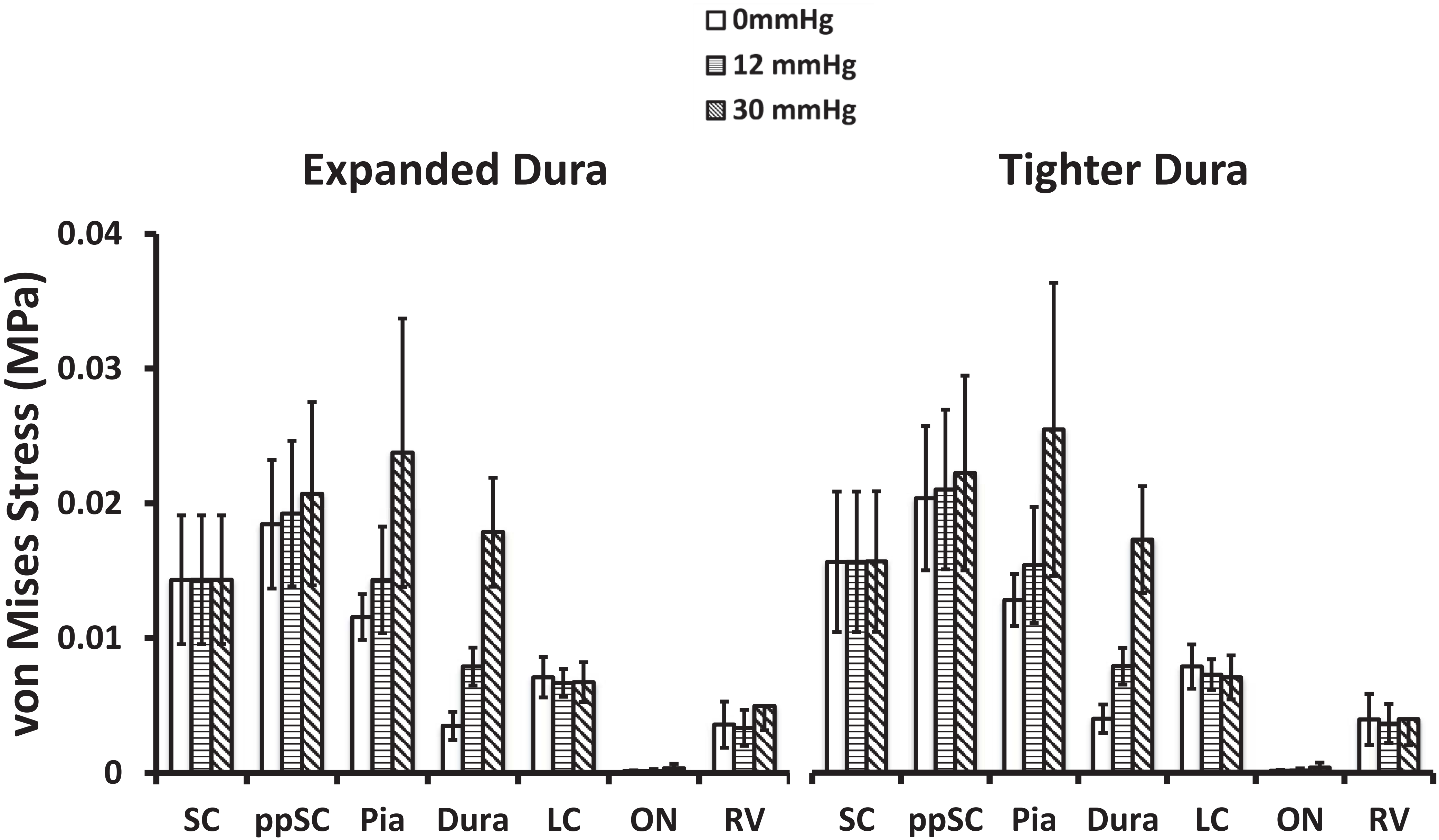
3. Elevated ICP

   IOP – 15 mmHg **ICP - 30 mmHg** RVP – 55 mmHg

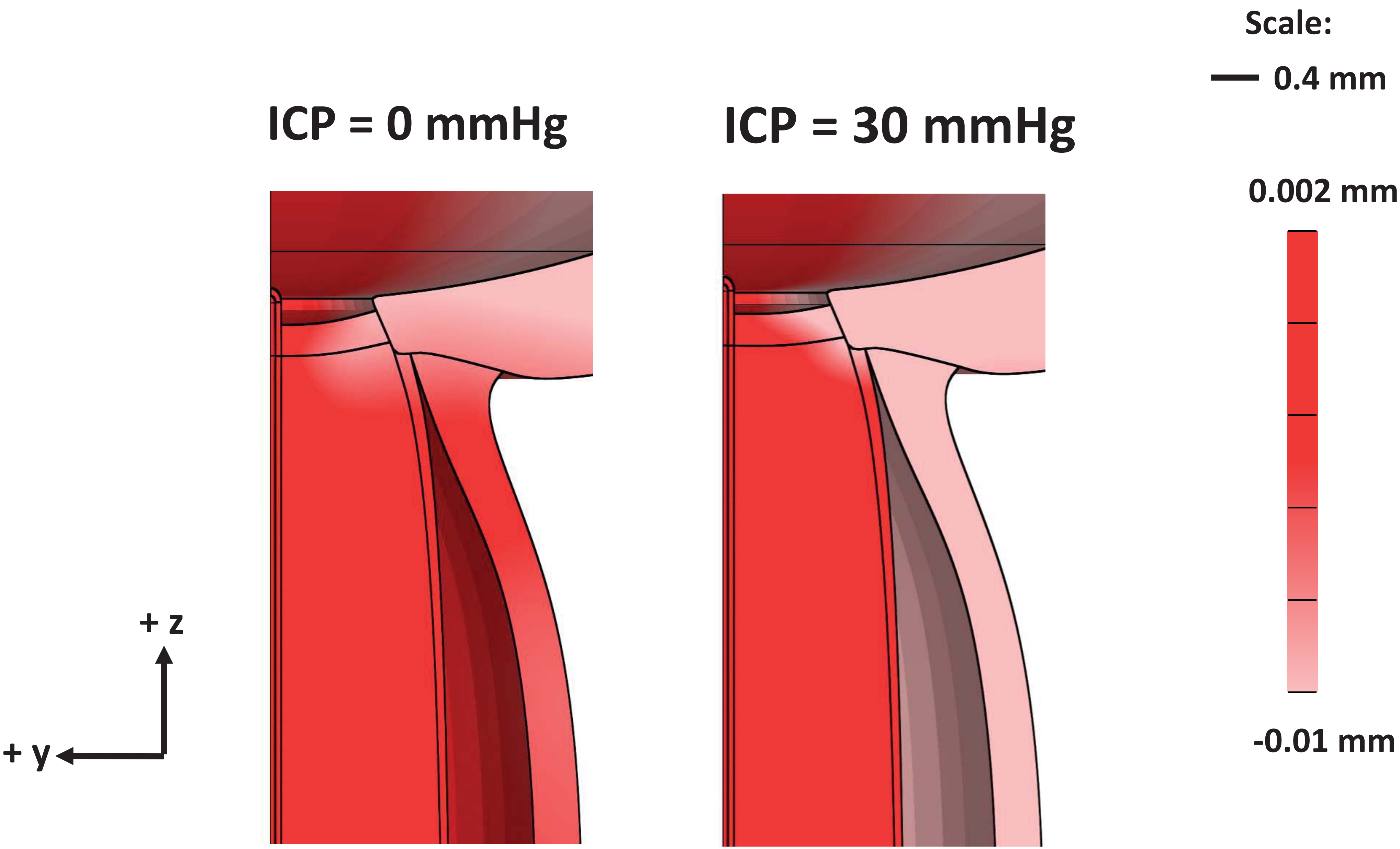
# von Mises Stress



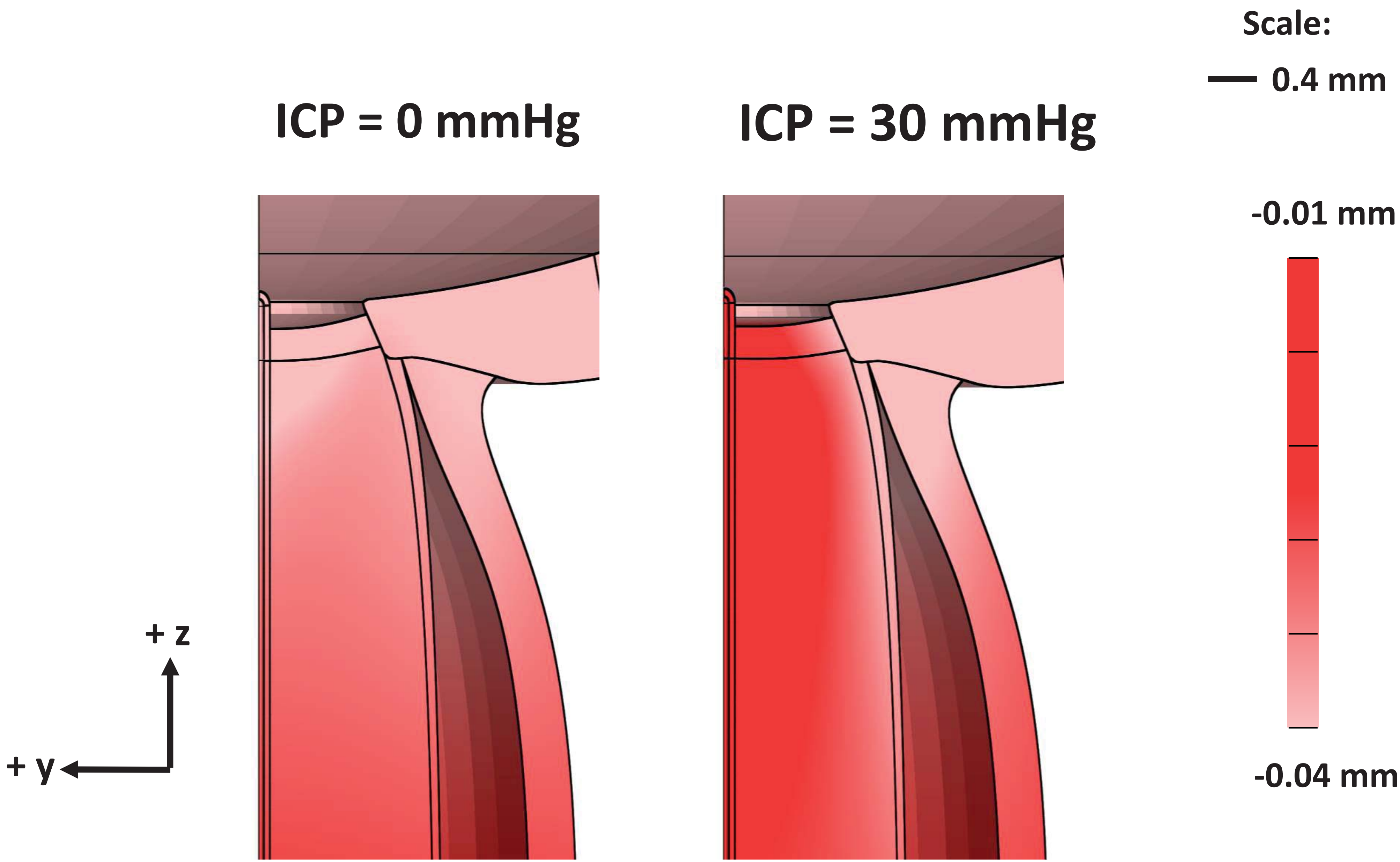
# von Mises Stress Distributions



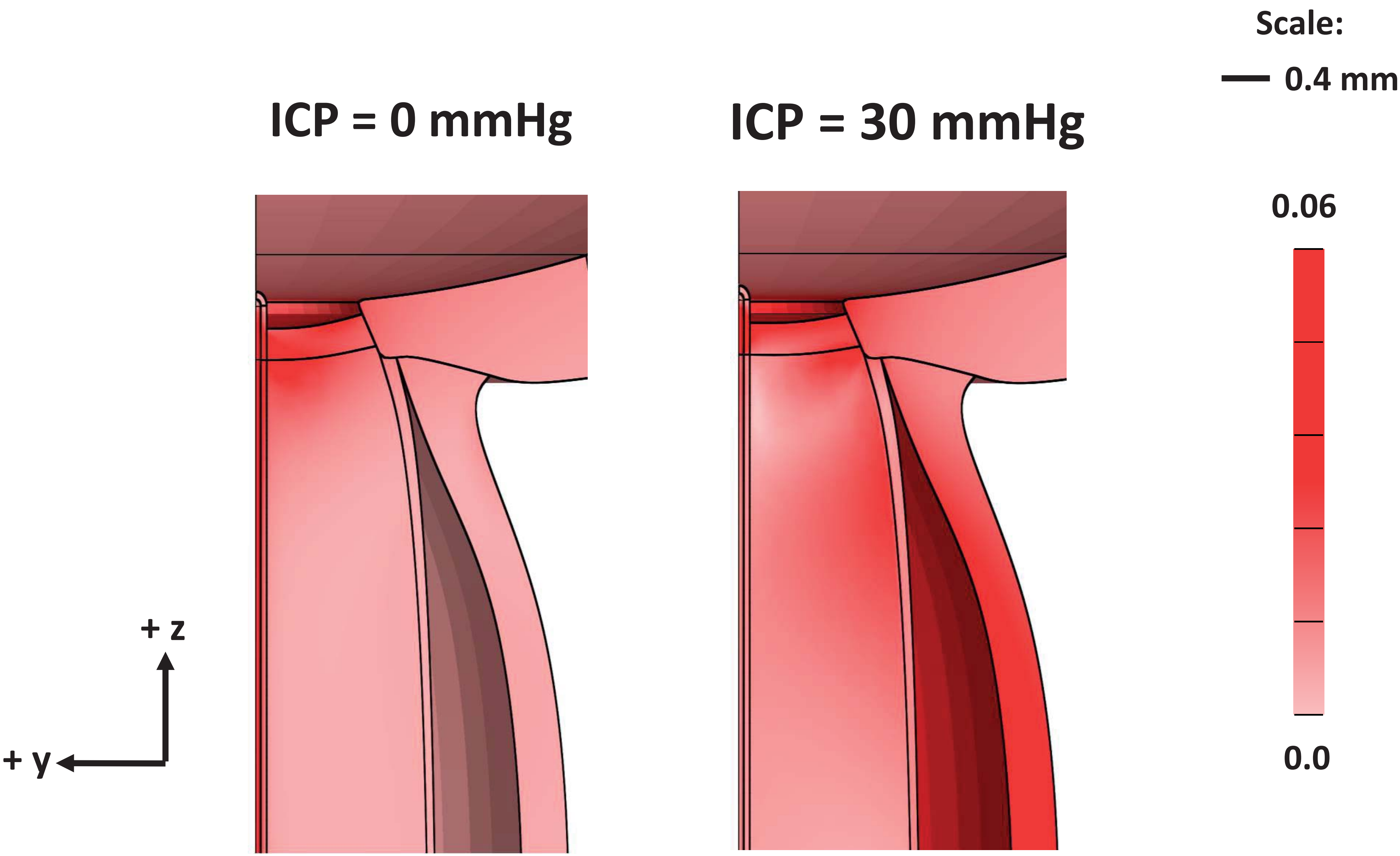
# Y-displacement



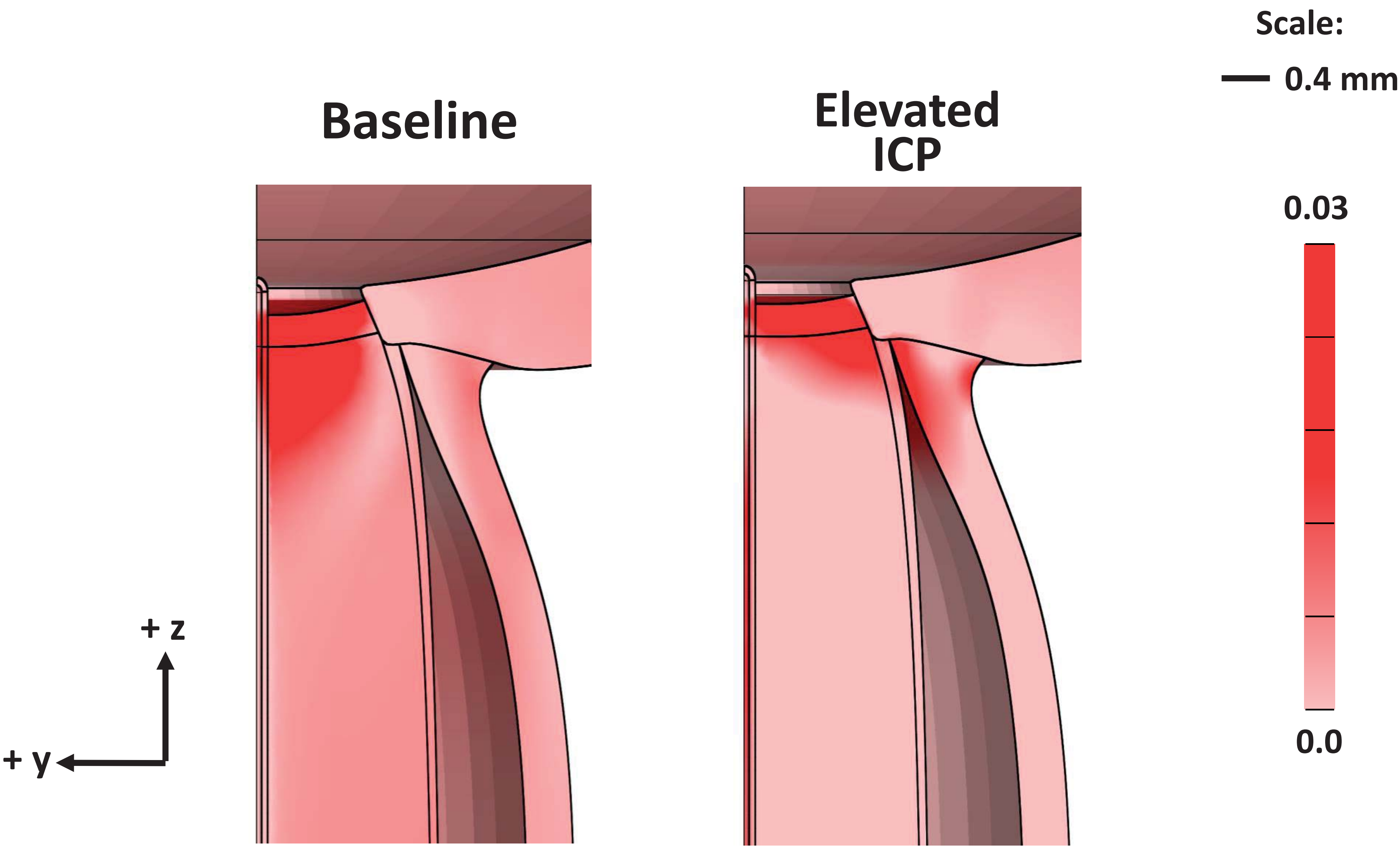
# Z-displacement



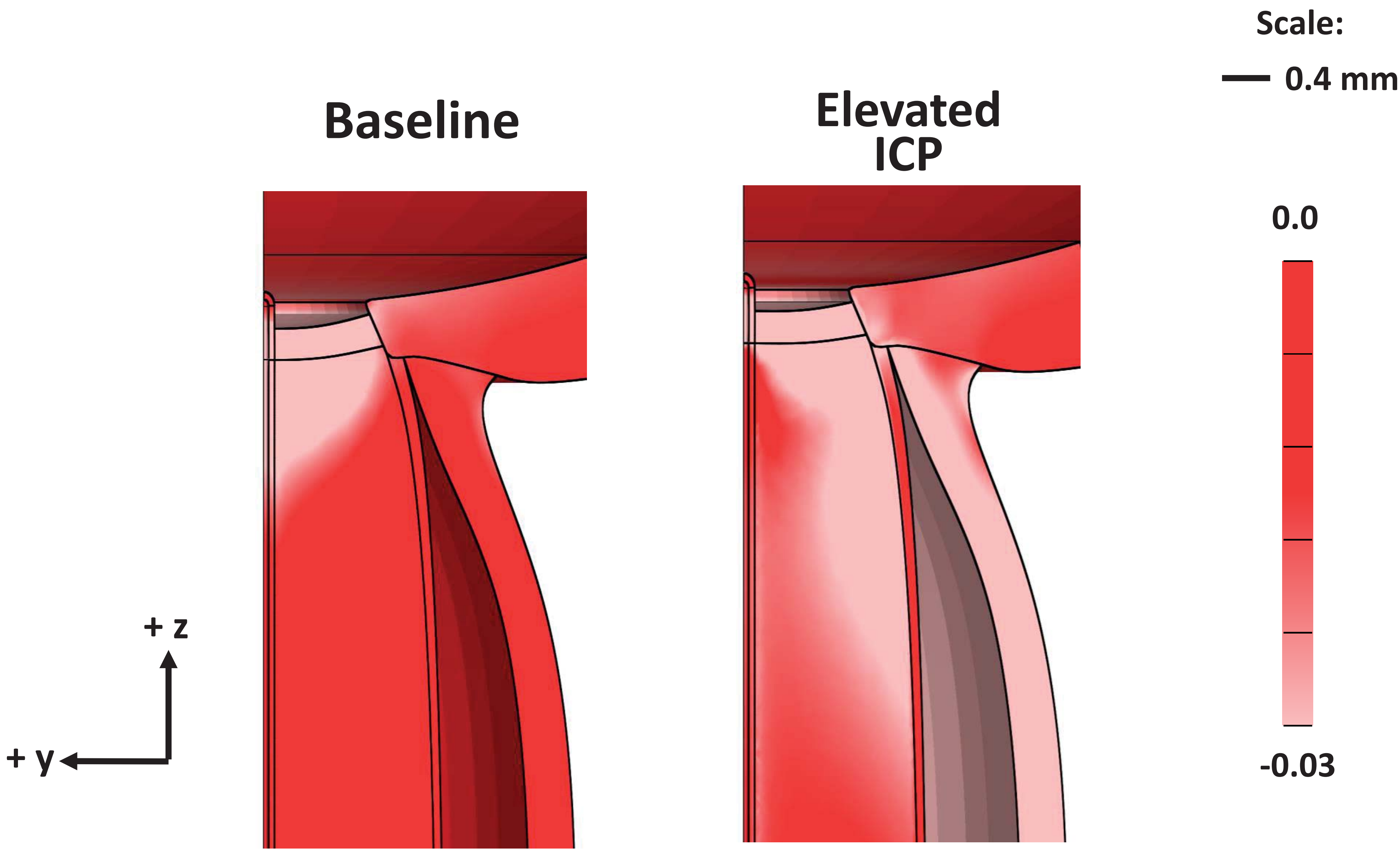
# 1st Principal Strain



# 2nd Principal Strain

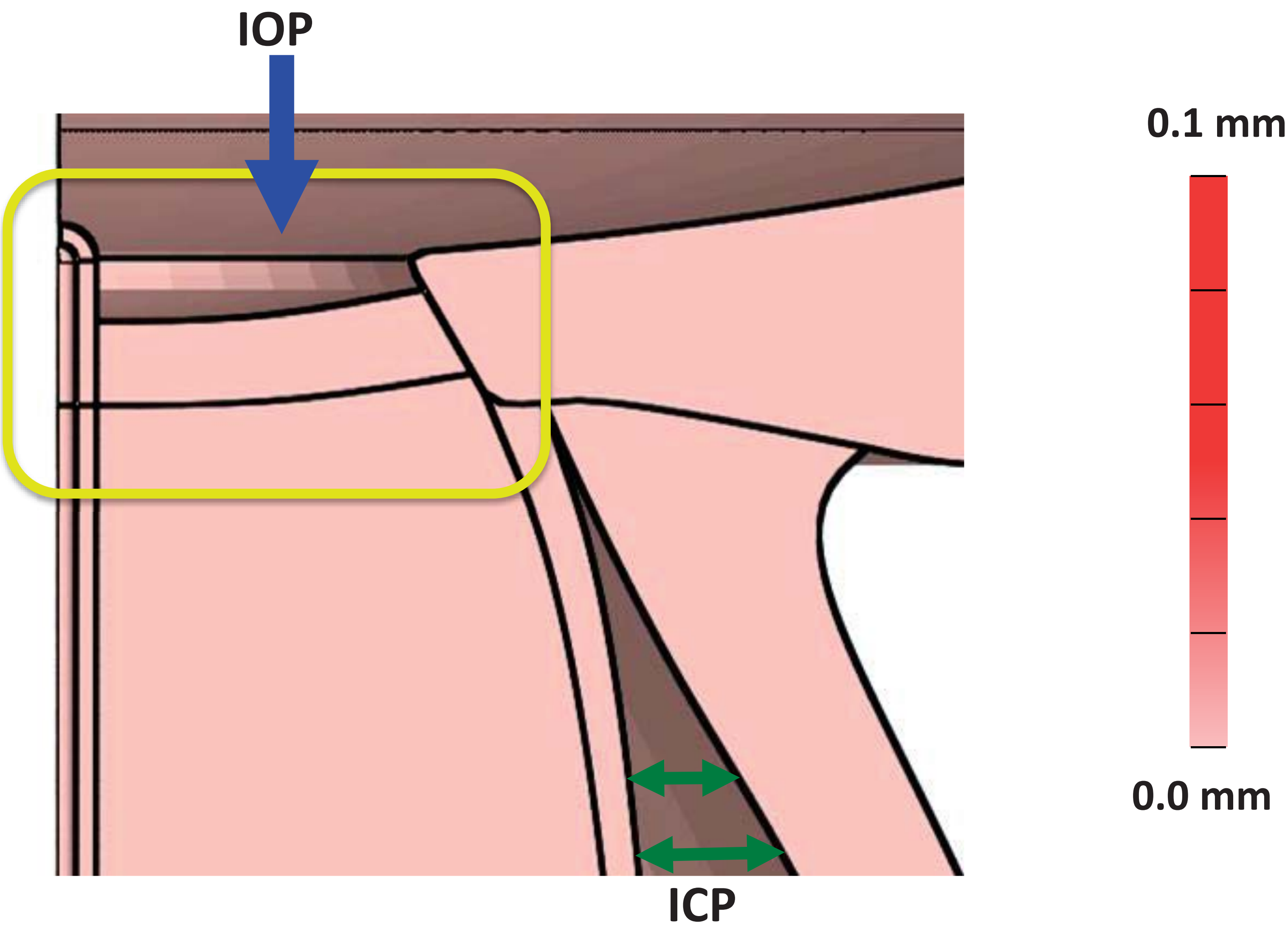


# 3rd Principal Strain



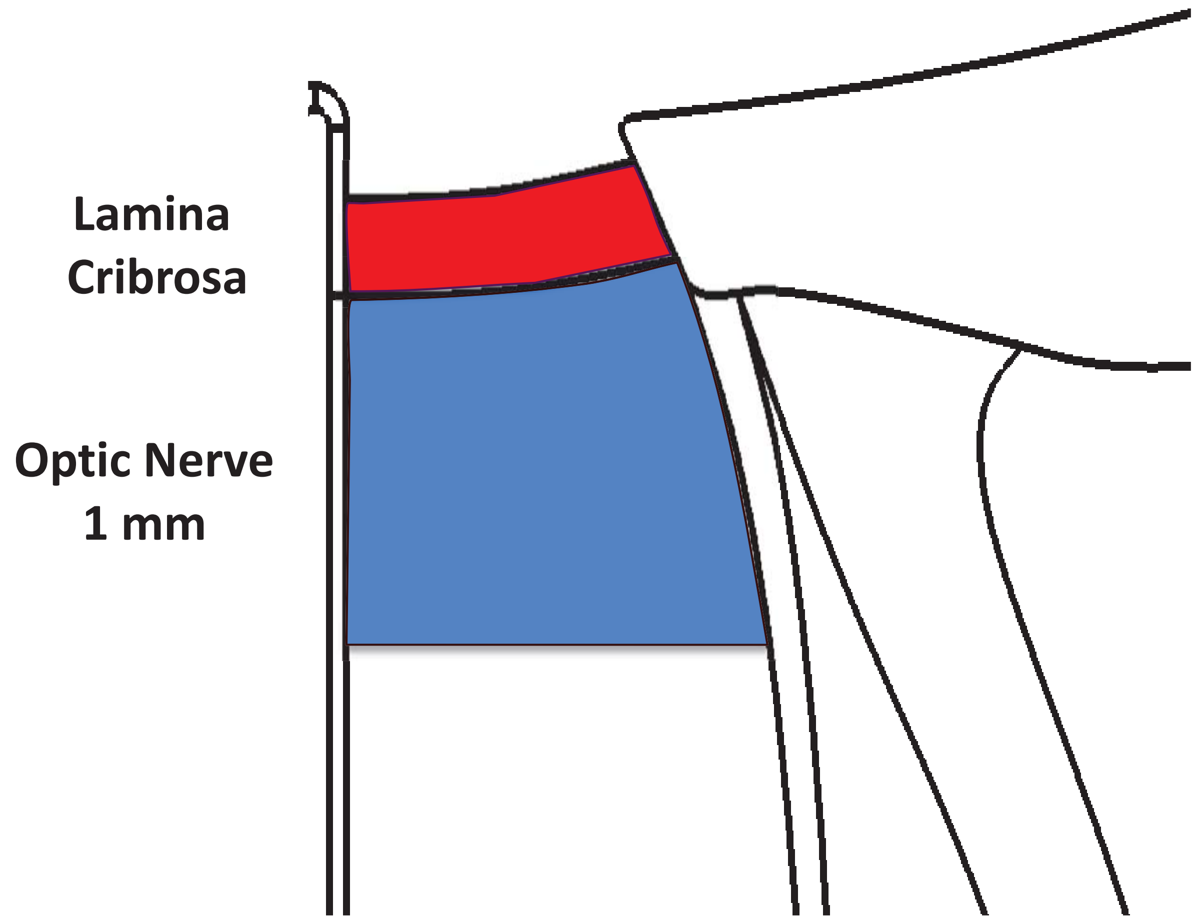
# Displacements

## Increase ICP: 0 to 30 mmHg




* Color scale is total displacement

# Regions of Interest

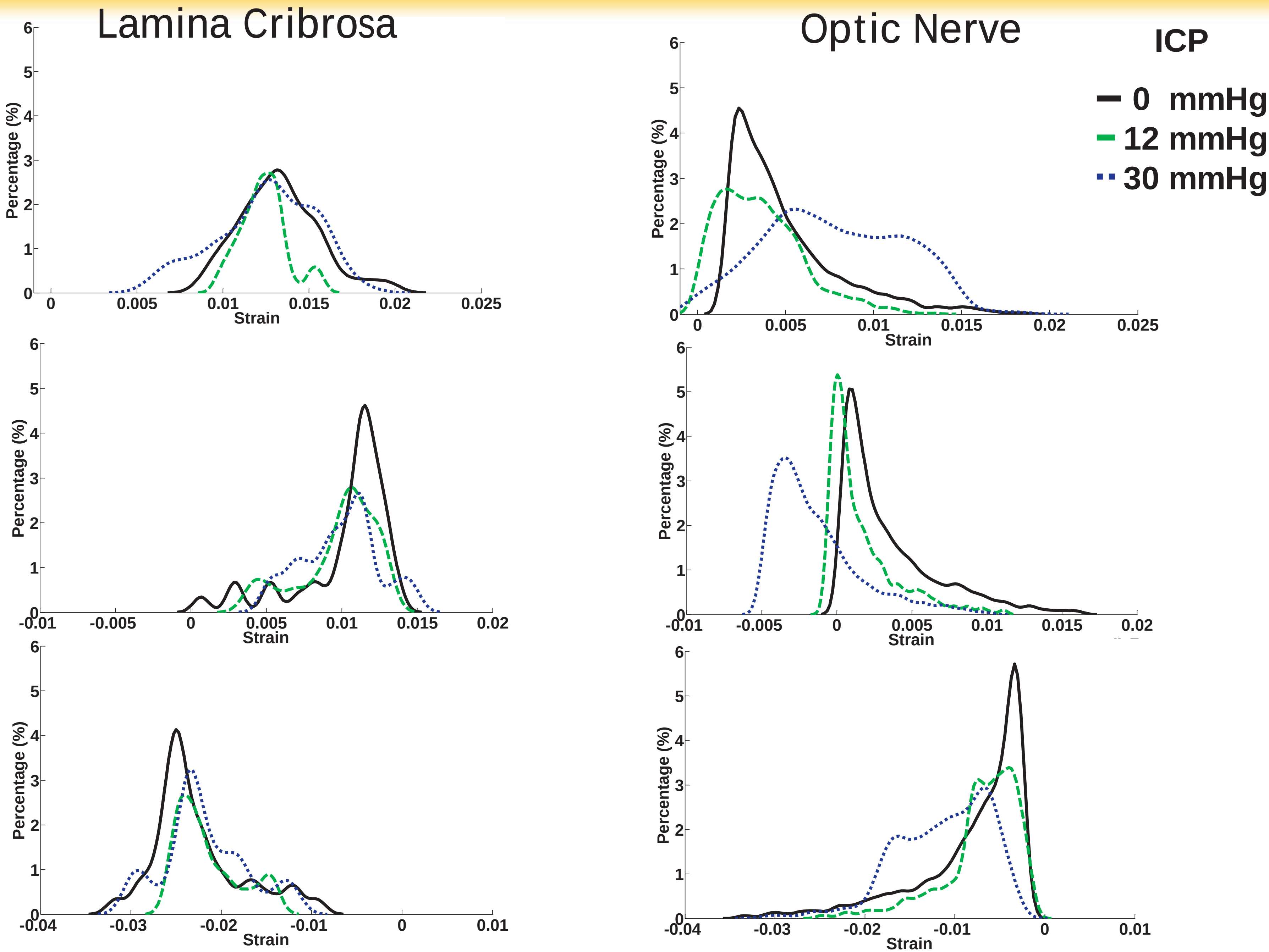


# Principal Strain Distributions

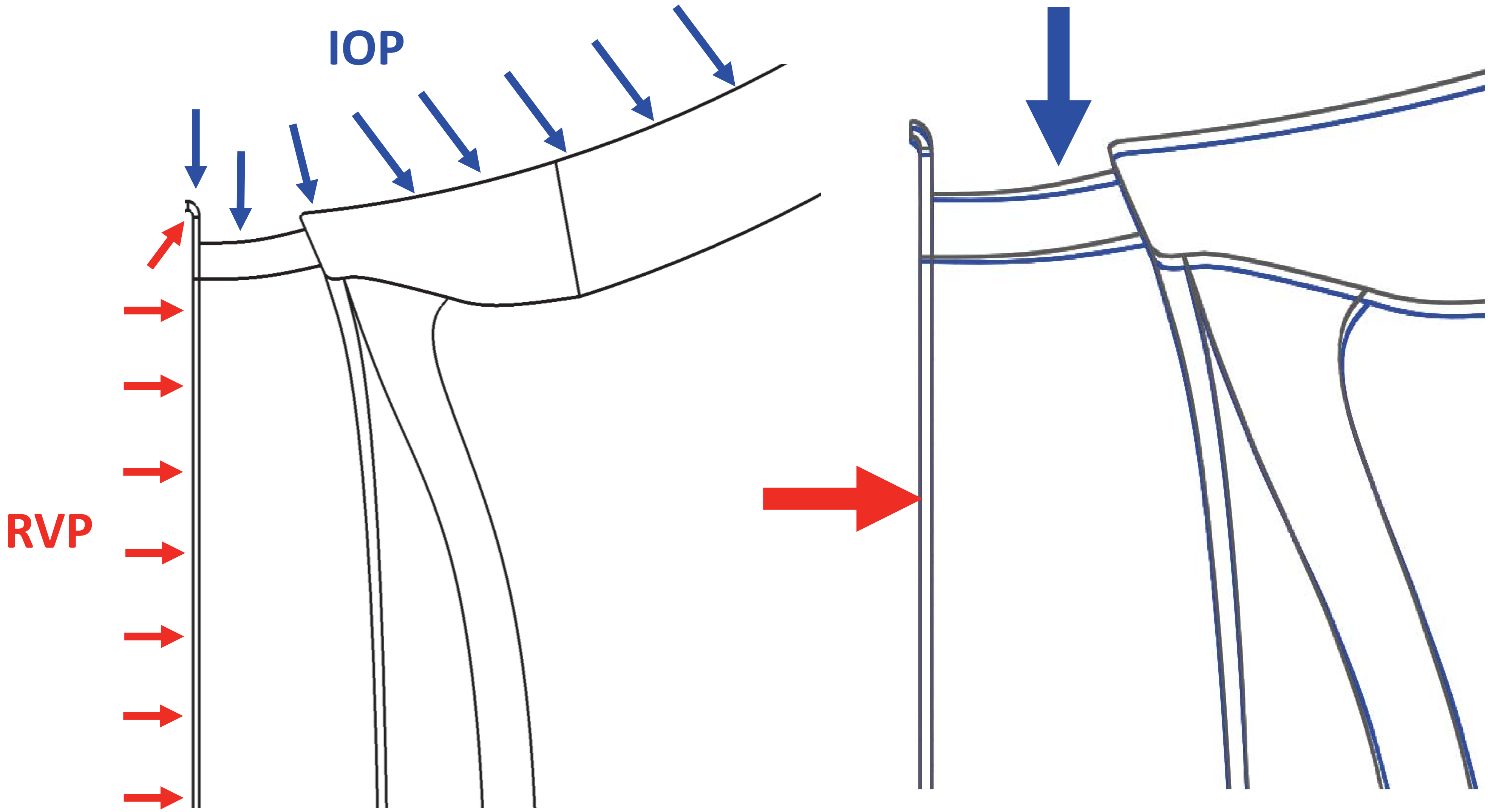
1st Principal Strain

2nd Principal Strain

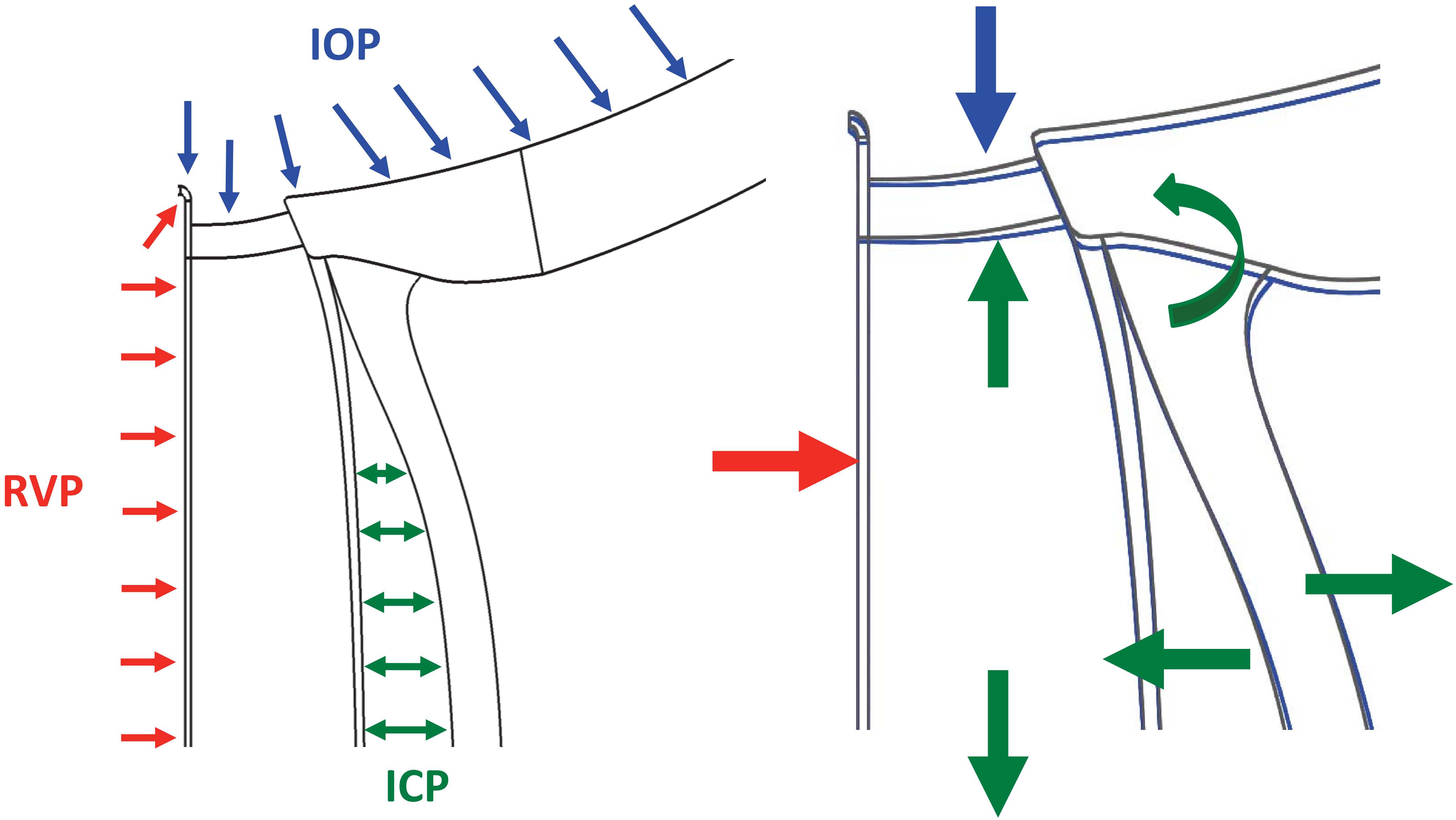
3rd Principal Strain



# Schematic Description

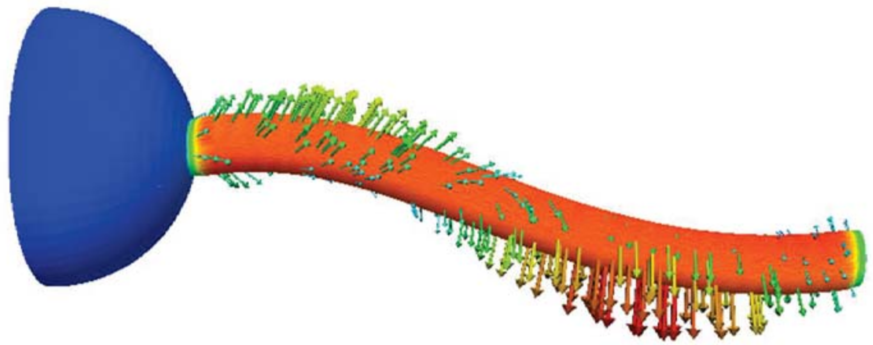


# Schematic Description



# Future Directions

- Quantify collagen microstructural changes during mechanical loading
- Incorporate collagen microstructure into computational models of VIIP syndrome
- Study possible static instability in ONS



# Acknowledgements

- DeVon Griffin
- Ian Sigal
- **Andrew Feola**

DIGITAL ASTRONAUT PROJECT

HUMAN RESEARCH PROGRAM

NASA

EMORY

PARKER H. PETIT INSTITUTE FOR BIOENGINEERING AND BIOSCIENCE IBB

UAB THE UNIVERSITY OF ALABAMA AT BIRMINGHAM

Georgia Institute of Technology