Modeling the Effects of Spaceflight on the Posterior Eye in VIIP

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Commercial Relationships Disclosure

No relationships to disclose for any co-author

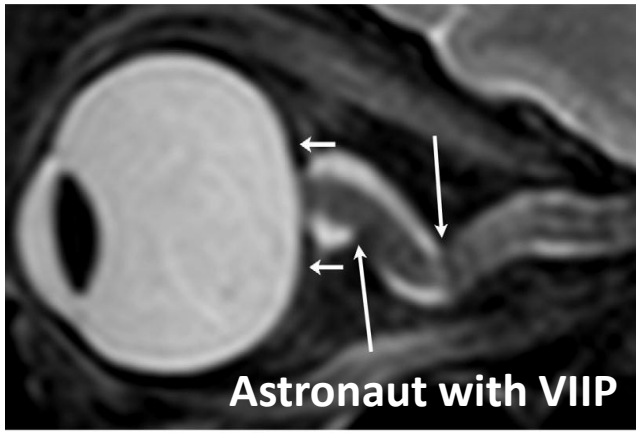
Funding support

- NASA Grant NNX13AP91G
- Georgia Research Alliance

VIIP Syndrome

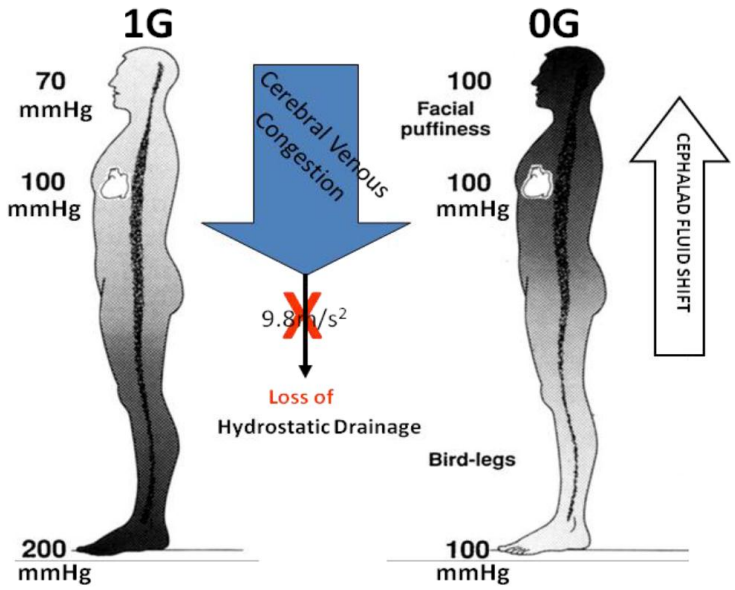
Permanent changes in visual function/ocular anatomy after long-duration space flight

- 41.7% incidence in U.S. astronauts
- Choroidal folds, papilledema, globe flattening, optic nerve dura distention/kinking



Kramer et al. Radiology, 2012.

Hypothesis



humanresearchroadmap.nasa.gov

Increased intracranial pressure (ICP) due to cephalad fluid shift leads to:

- Connective tissue remodeling in the posterior eye/optic nerve sheath
- Mechanical loading/insult to ONH cells and tissues, and eventual vision loss

Goal

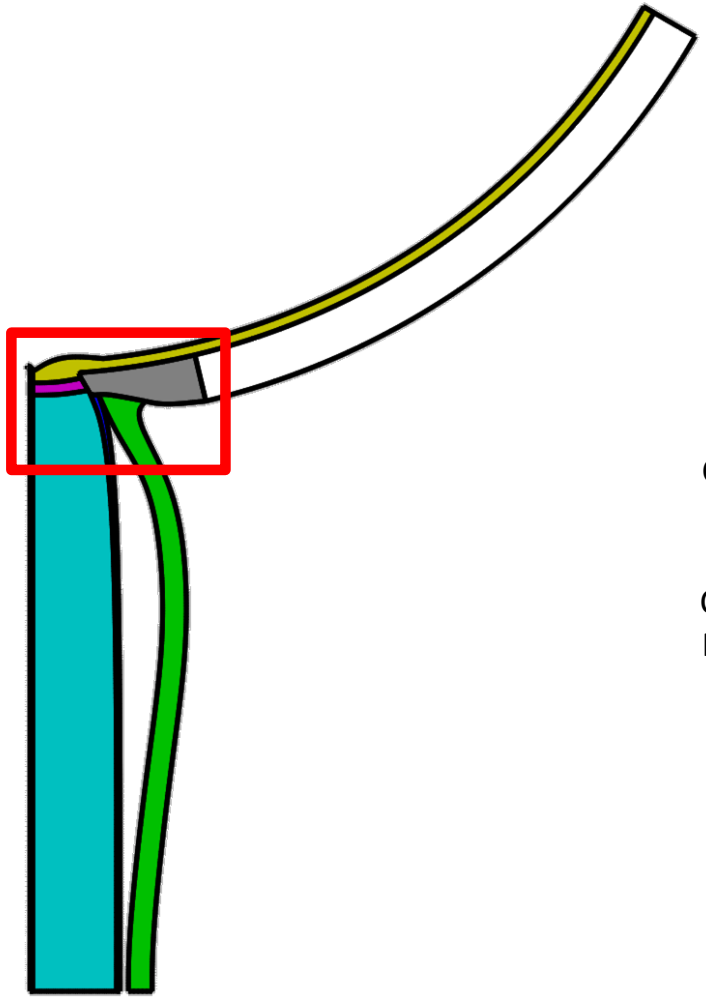
Study the biomechanical response of the optic nerve sheath and posterior eye to changes in ICP

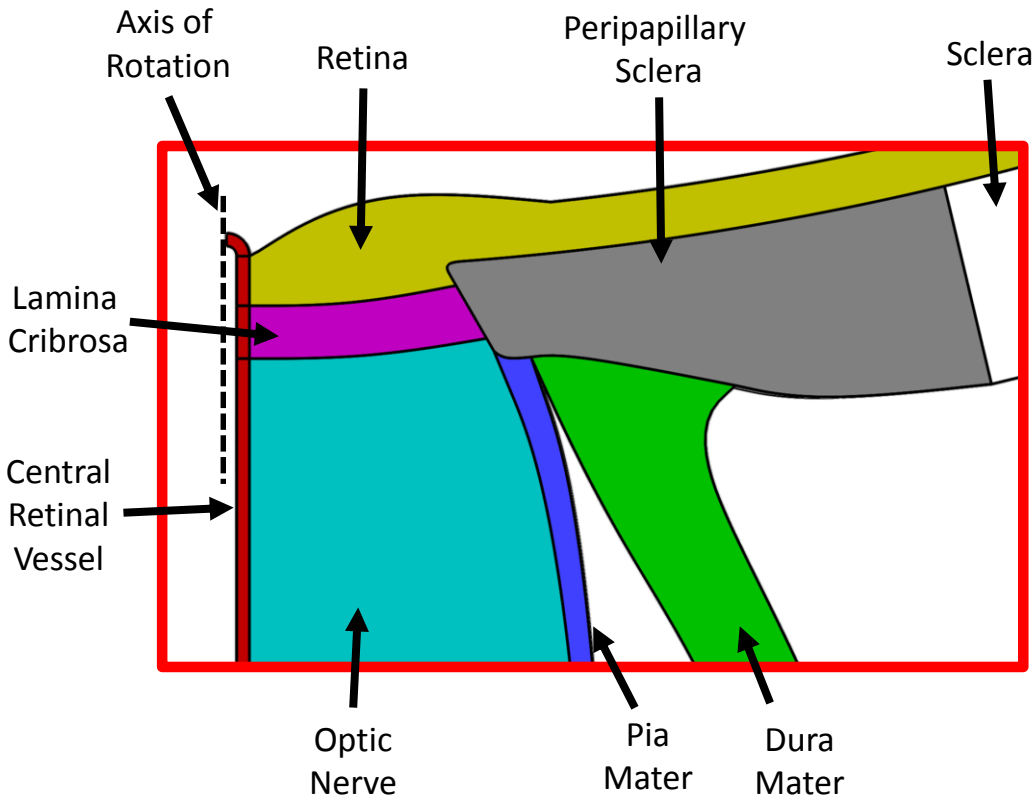
- Account for different ICP “cases”
  - Terrestrial supine
  - Terrestrial standing
  - Microgravity (presumed elevated ICP)
- Account for variations of ICP within these cases
- Account for variations in tissue properties

Methods

COMPUTATIONAL (FINITE ELEMENT) MODEL

Model Geometry



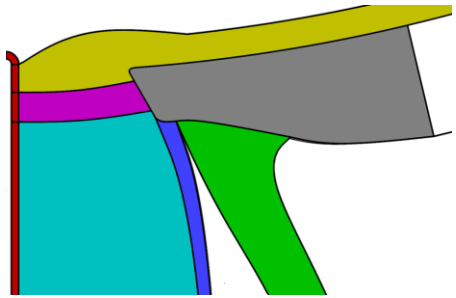


Model Inputs

Name	Abbreviation	Units	Baseline	Standard Deviation	Low	High
Pressures						
Intraocular Pressure	IOP	mmHg	15	1.85	10	19
Intracranial Pressure	ICP	mmHg				
Upright			0	2.0	-4	4
Supine			10	2.0	6	14
Elevated			20	2.5	15	25
Mean Arterial Pressure	MAP	mmHg	86	7.96	60	112
Biomechanical Properties						
Sclera Young's modulus	SC	MPa	5		1	9
Peripapillary Sclera Young's modulus	ppSC	MPa	5		1	9
Lamina Cribrosa Young's modulus	LC	MPa	0.5		0.1	0.9
Pia Mater Young's modulus	Pia	MPa	5		1	9
Dura Mater Young's modulus	Dura	MPa	1		0.2	2
Optic Nerve Young's modulus	ON	MPa	0.05		0.01	0.09
Retina Young's modulus	Ret	MPa	0.05		0.01	0.09
Retinal Vessel Young's modulus	RV	MPa	0.3		0.2	0.4
Neural Poisson's ratio	Poisson's	-	0.45		0.4	0.49

Latin hypercube sampling

Efficiently simulates variation in input parameters (Monte Carlo)



Outcome measure

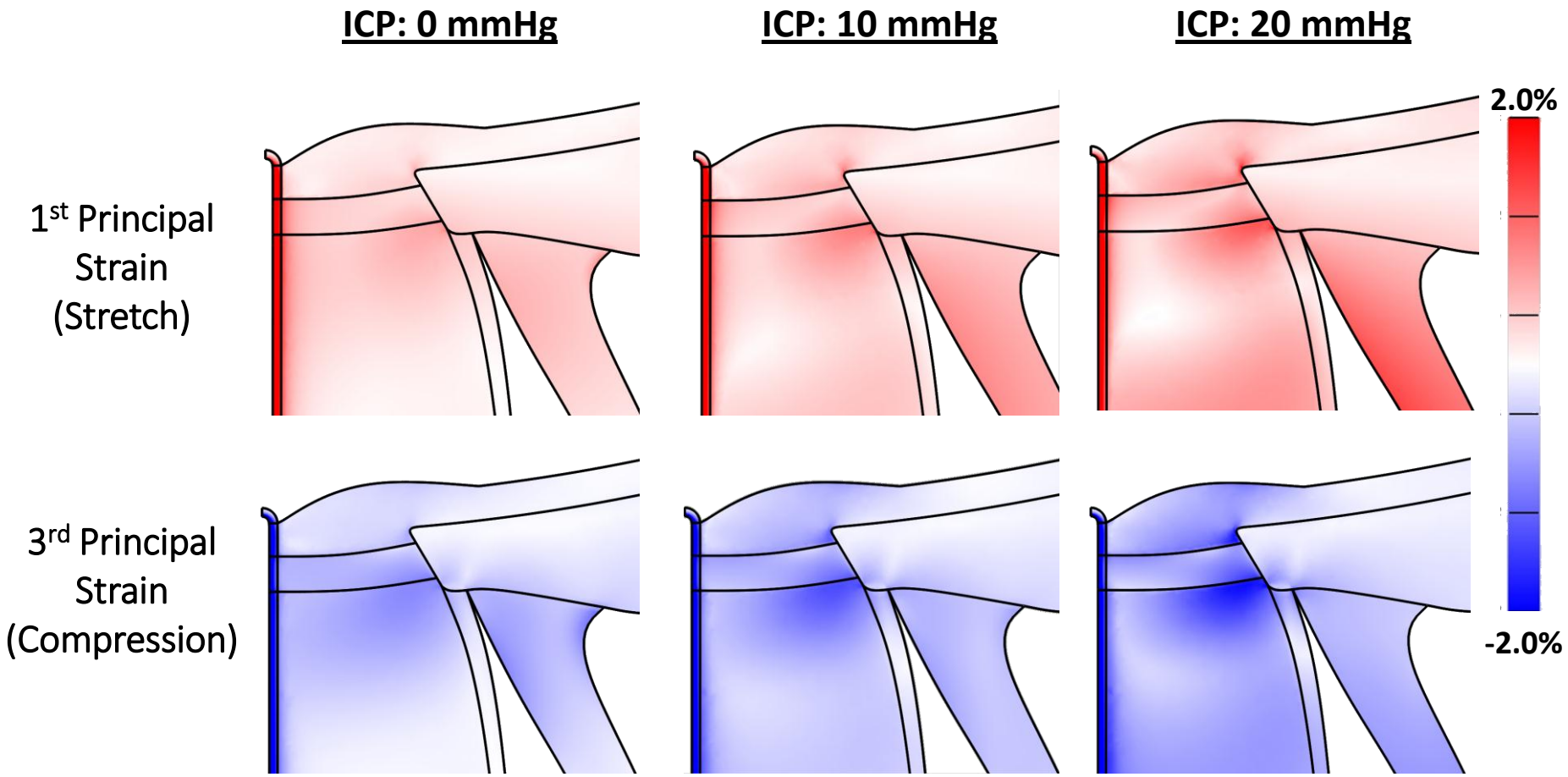
Strain in ONH tissues

- Physical quantity that represents stretching of cells and tissues
- Local cells are mechanoresponsive
- Strain drives connective tissue remodeling in many other tissues, e.g. artery walls

Results

COMPUTATIONAL (FINITE ELEMENT) MODEL

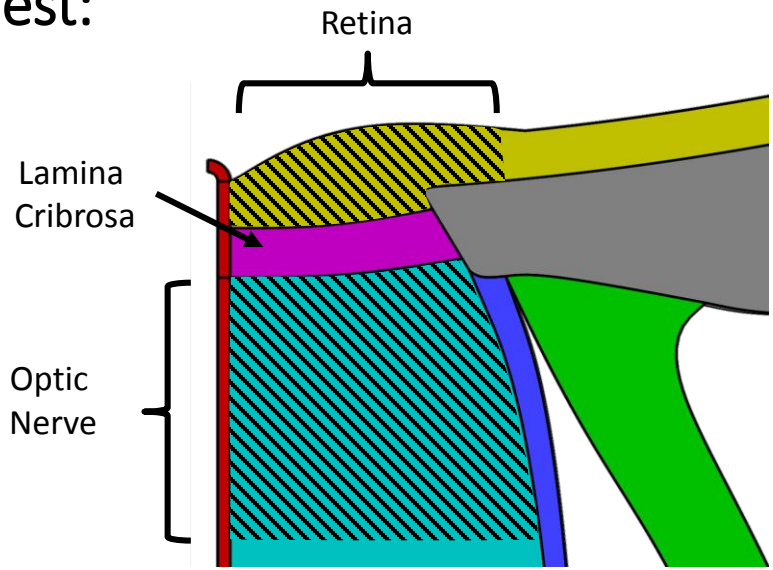
Effect of ICP: Baseline case



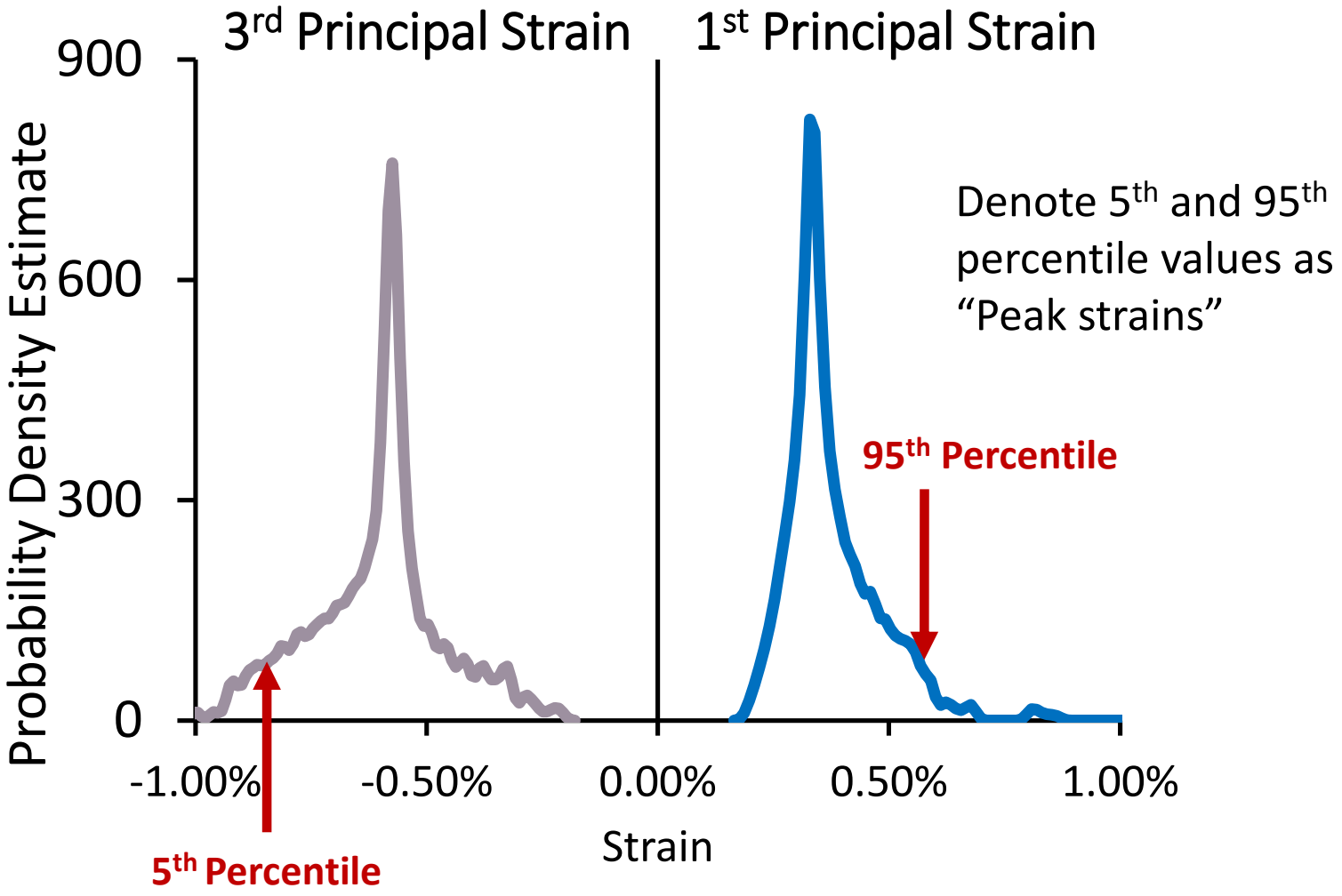
Average strains: Baseline case

Tissue Region:	Lamina Cribrosa		Optic Nerve		Retina	
Strain Type:	Tension	Compression	Tension	Compression	Tension	Compression
ICP = 0 mmHg	0.57%	-0.86%	0.61%	-0.85%	0.35%	-0.48%
ICP = 10 mmHg	0.78%	-1.11%	0.78%	-1.21%	0.63%	-0.83%
ICP = 20 mmHg	0.97%	-1.35%	0.96%	-1.56%	0.91%	-1.21%

Regions of Interest:

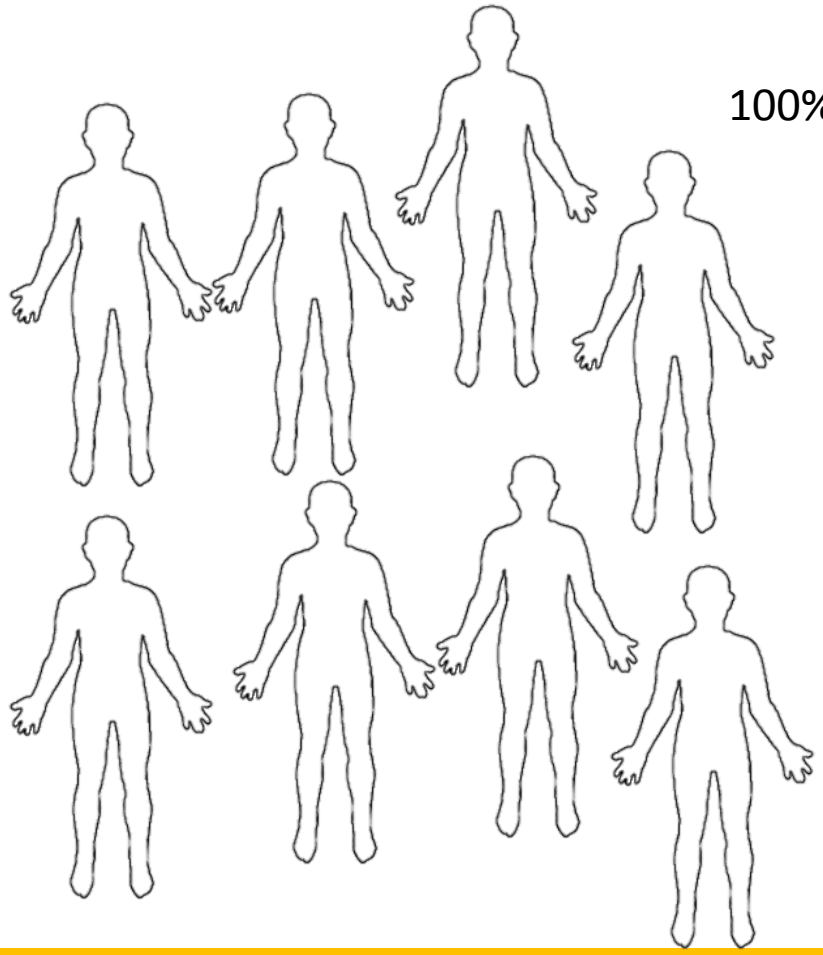


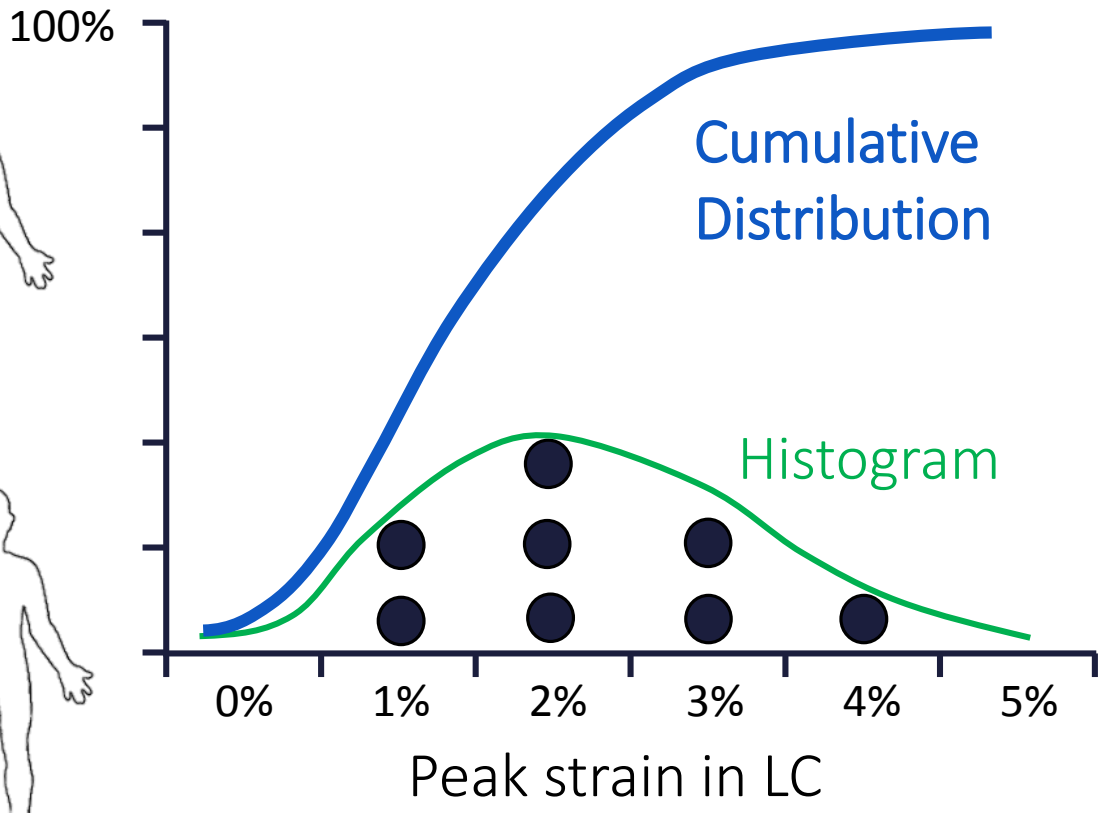
Lamina Cribrosa Strain Histograms



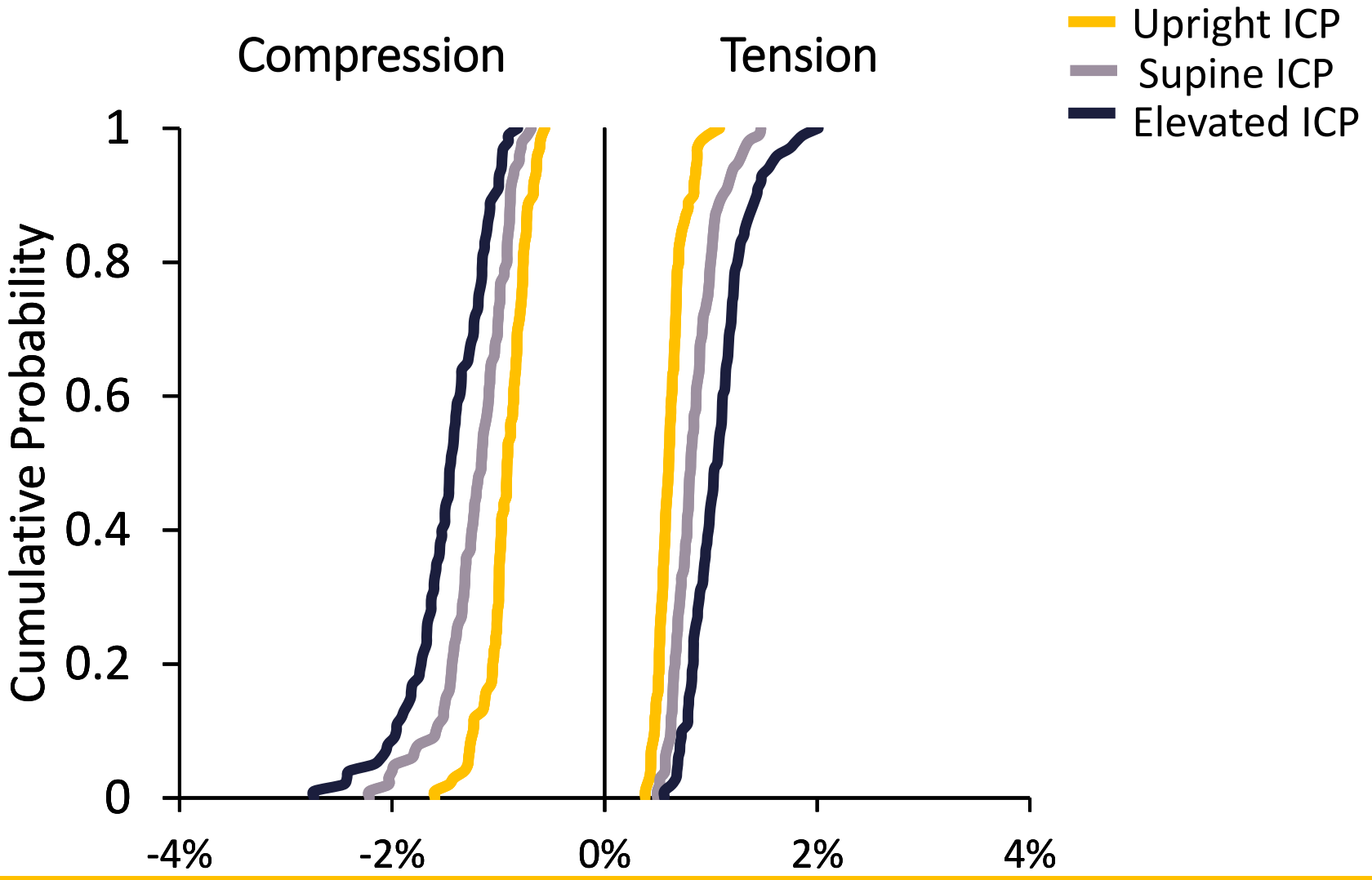
Distribution within population

Use Latin Hypercube Sampling

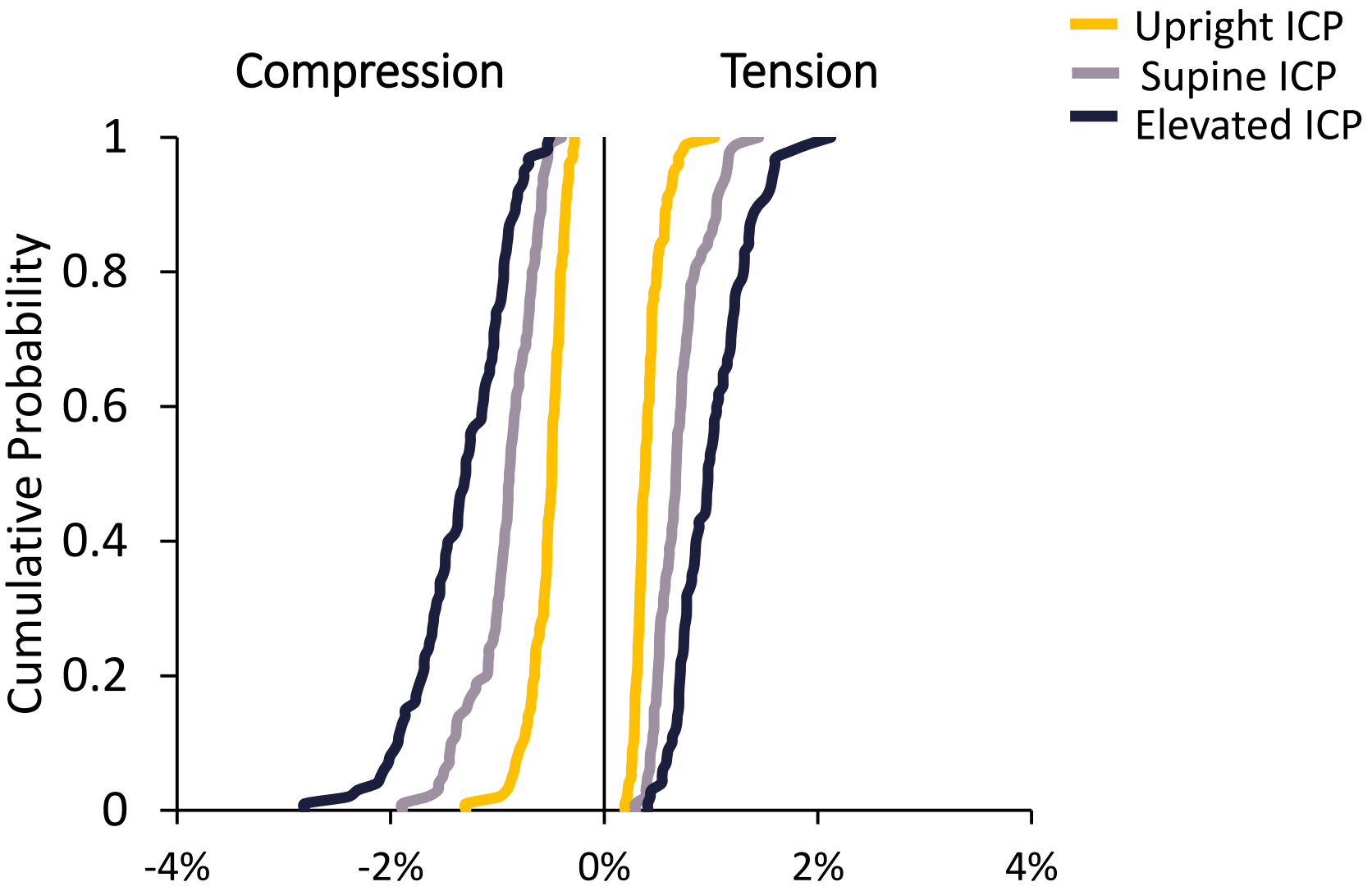




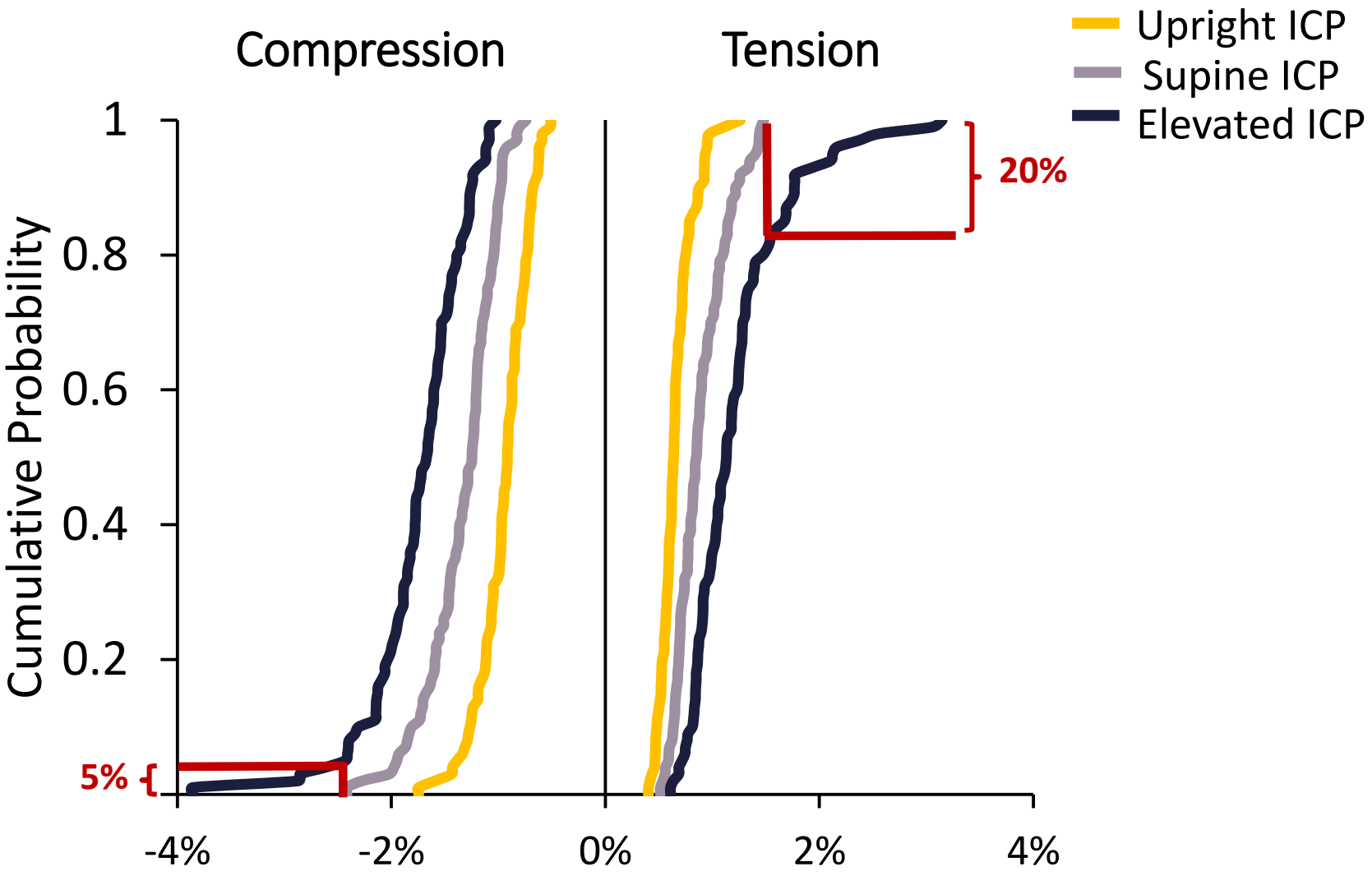
“Peak” Strains in Lamina Cribrosa



“Peak” Strains in Retina



“Peak” Strains in Optic Nerve



“Out of this World Strains”

Tissue Region:	Lamina Cribrosa		Optic Nerve		Retina	
Strain Type:	Tension	Compression	Tension	Compression	Tension	Compression
Supine	8%	5%	20%	6%	10%	13%

Percentage of individuals with elevated ICP experiencing strains larger than those experienced under terrestrial conditions (standing or supine)

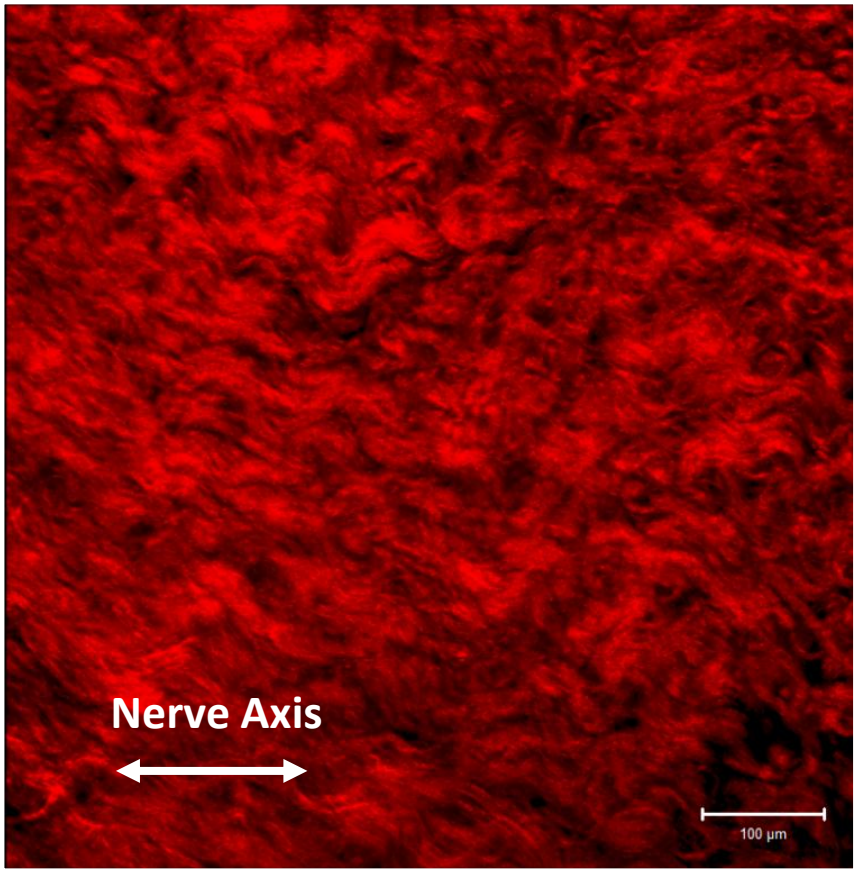
Optic Nerve Sheath

EXPERIMENTAL MEASUREMENTS

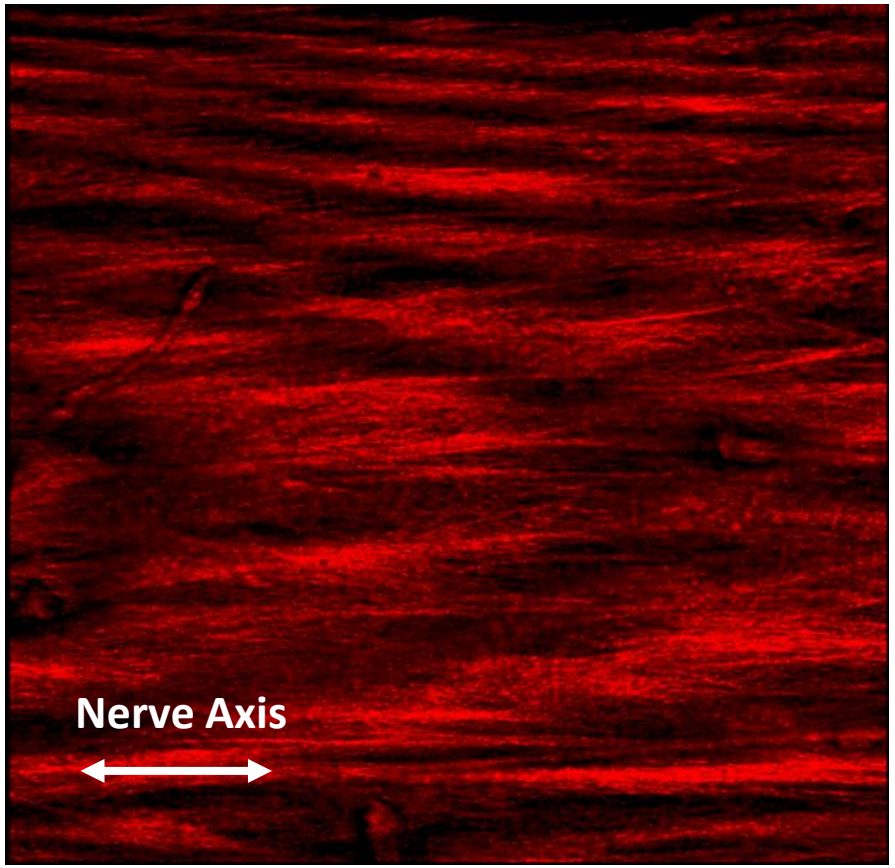
Collagen orientation in dura

SHG microscopy images of dura

0 mm Hg



10 mm Hg



Optic nerve has slack

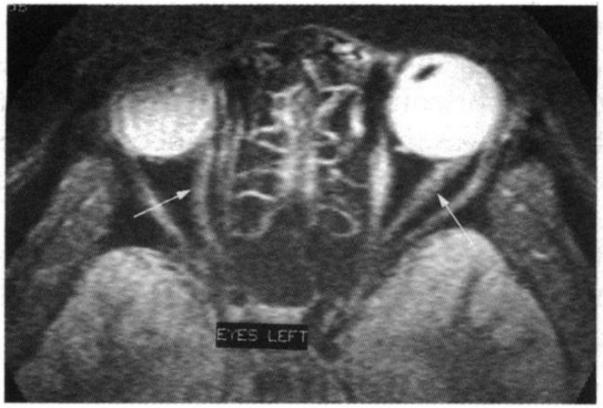


Fig 5A

Fig 5B

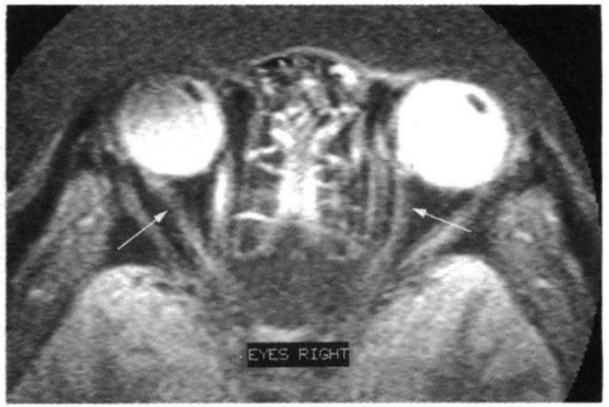
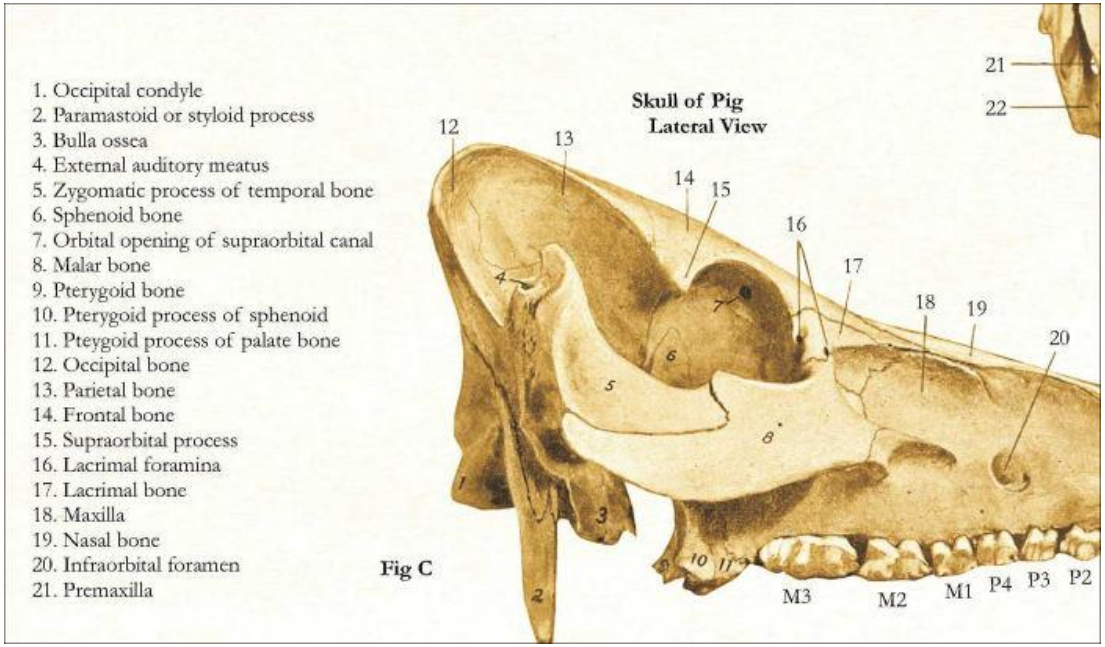


Fig 5C

Liu et al., BJO, 1992

What is state of ON stretch?

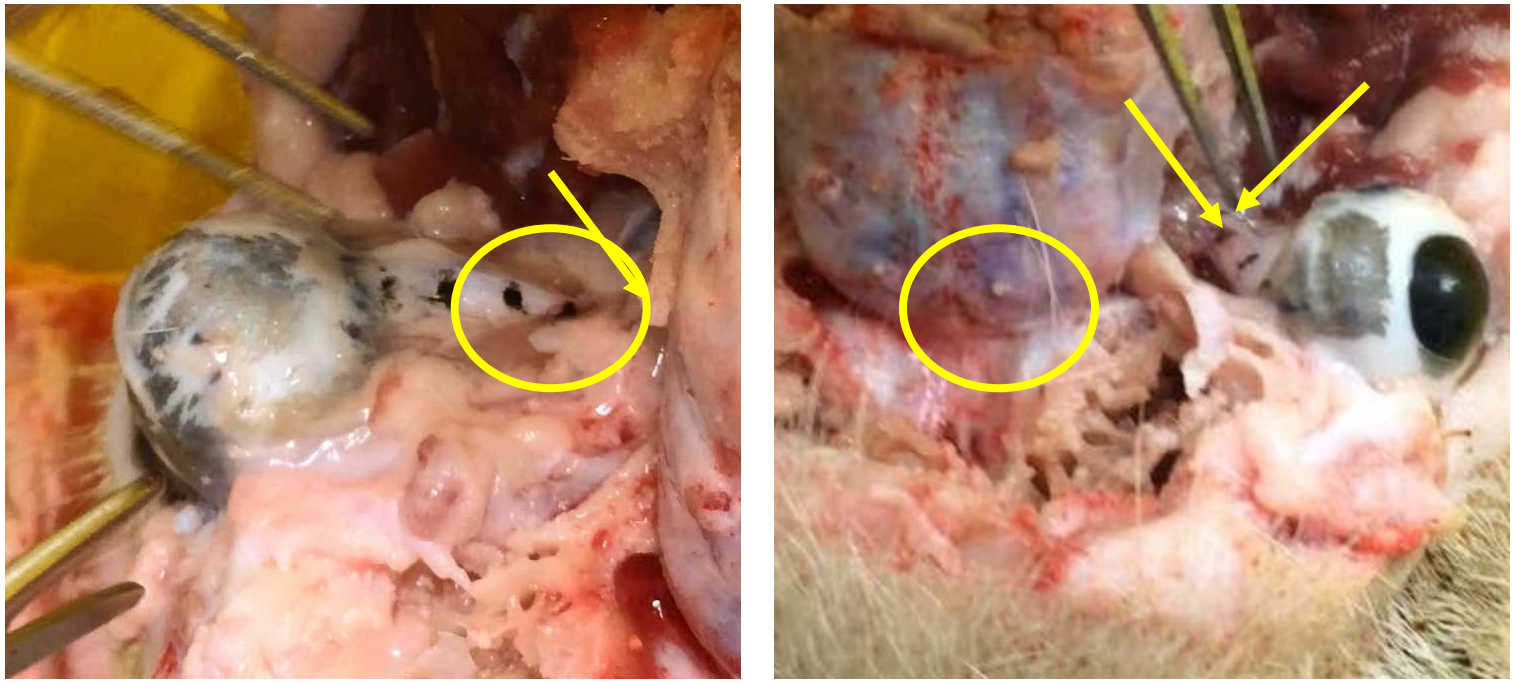
Expose optic nerve, transect, observe retraction (or not)



http://www.dcfirst.com/pig_anatomy_poster.html

Perform craniotomy → Expose orbit → Remove periorbital tissue covering the optic nerve → Place markers on the optic nerve → Transect nerve and record axial retraction

Optic nerve retraction



Summary

ICP affects strains in ONH tissues:

- Average strain values are low
- Simulation of “population” shows that 5-20% of individuals will experience ICP-induced strains in space that are more extreme than those on earth

Uncertainties/Limitations

- Optic nerve appears to be under tension (?!)
- Some tissue properties still not well understood
- Pathophysiology of vision loss and connection with strain not established

BME at Georgia Tech/Emory