FINITE ELEMENT MODELING TECHNIQUES FOR ANALYSIS OF VIIP

A. Feola¹, J. Raykin¹, R. Gleason¹, L. Mulugeta³, J. Myers², E. Nelson², B. Samuels⁴, C.R. Ethier¹

¹Department of Biomedical Engineering, Georgia Institute of Technology/Emory University, Atlanta, GA; ²NASA Glenn Research Center, Cleveland, OH; ³Universities Space Research Association, Houston, TX; ⁴Department of Ophthalmology, U. Alabama at Birmingham, Birmingham, AL
• Clinical signs of microgravity in the eye and optic nerve:

  - Grade 3 edema
  - Choroidal folds
  - Posterior Globe Flattening
  - Optic Nerve ‘kinking’

-Mader et al. 2011; Kramer et al. 2012
Hypothesis

- Cephalad fluid shifts in microgravity affect intracranial and intraocular pressures, leading to altered biomechanical loads on the connective tissues of the posterior globe and optic nerve sheath.
• **Goal:** To model the response of the lamina cribrosa and optic nerve head (ONH) to elevated intracranial pressure (ICP)

• **Finite Element Analysis (FEA)**
  – Simulates effects of loads (pressures) on tissues with complex anatomy/material properties
  – Previously used to understand how IOP-induced changes affect the stresses and strains in the lamina cribrosa and ONH
Initial Steps

1. Develop geometry of the posterior eye
   – Including all relevant tissue components

2. Perform a mesh convergence study
   – To ensure mesh independence

3. Simulate pressures estimated to occur in microgravity
Optic Nerve Head (ONH) Geometry

- Based on models of Sigal et al., 2005

Adopted from Liu and Kahn 1993
• Our anatomical geometry is axisymmetric but it was required to be modeled as a 3D wedge in the FE solver (FEBio)
  – Defined in-plane (y and z) and circumferential (s) element sizes
Model Overview

- All tissues were modeled as isotropic, linear-elastic and incompressible.

<table>
<thead>
<tr>
<th>Component</th>
<th>Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sclera</td>
<td>3.0</td>
</tr>
<tr>
<td>Peripapillary sclera</td>
<td>3.0</td>
</tr>
<tr>
<td>Lamina cribrosa</td>
<td>0.3</td>
</tr>
<tr>
<td>Optic nerve</td>
<td>0.03</td>
</tr>
<tr>
<td>Pia mater</td>
<td>3.0</td>
</tr>
<tr>
<td>Dura mater</td>
<td>1.0</td>
</tr>
<tr>
<td>Central retinal vessel</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- Raykin et al. 2013; Sigal et al. 2004; Sigal et al. 2005
Boundary Conditions

- Intraocular Pressure (IOP)
- Retinal Vessel Pressure (RVp)
- Intracranial Pressure (ICP)
Convergence Overview

- The average effective strain for each tissue region was calculated for each mesh density.

- **Convergence Criteria:** Our production mesh was defined as having \(<5\%\) relative error in the average effective strain from our most refined mesh.

<table>
<thead>
<tr>
<th>Component</th>
<th>Number of Elements (Hexahedral)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sclera</td>
<td>689 – 7589</td>
</tr>
<tr>
<td>Peripapillary sclera</td>
<td>560 - 21145</td>
</tr>
<tr>
<td>Lamina cribrosa</td>
<td>265 - 13565</td>
</tr>
<tr>
<td>Optic nerve</td>
<td>8445 - 52147</td>
</tr>
<tr>
<td>Pia mater</td>
<td>662 – 53662</td>
</tr>
<tr>
<td>Dura mater</td>
<td>1835 – 44035</td>
</tr>
<tr>
<td>Central retinal vessel</td>
<td>243 - 126177</td>
</tr>
</tbody>
</table>
Lamina Cribrosa Convergence Plot

**Methods**

- Lamina Cribrosa Convergence Plot
- Production Mesh

**Graph Details**

- **Effective Strain (%)**
  - Y-axis range: 0.049 to 0.056
- **Element Size (mm)**
  - X-axis range: 0.001 to 1
- **Legend**
  - In-plane y
  - In-plane z
  - Circumferential
Estimated Pressures in Microgravity

- Intraocular Pressure (IOP) - 15 mmHg
- Retinal Vessel Pressure (RVp) - 55 mmHg
- Intracranial Pressure (ICP) - 30 mmHg

~ Alexander et al. 2012; Mader et al. 2011
Linear Elastic Model

First Principal Strain

- ICP: 0 mmHg
- ICP: 30 mmHg

Third Principal Strain

- 5 %
- -5 %
Conclusions

• Developed a physiologically relevant model of the posterior eye and optic nerve sheath
  – Performed a mesh convergence study

• We observed that elevating ICP alters the loading conditions in the optic nerve head
  – This may activate mechanosensitive cells and lead to a remodeling of the optic nerve sheath

• However linear-elastic materials may not completely describe the loading conditions of the eye in microgravity.
Poroelastic Models

• We explored implementing poroelastic materials and fluid loading conditions because:
  – The intraocular, retinal vessel, and intracranial pressures are generated by fluids
  – Poroelastic models allow volumetric changes when subjected to a fluid pressure
  – Fluid movement occurs between and within each tissue
Simulated the IOP and ICP as fluid pressures
We modeled the components of the optic nerve head as poroelastic
- The lamina cribrosa, optic nerve, and pia mater were poroelastic with a permeability of 0.001 mm²/MPa*s

- Raykin et al. 2013
First Principal Strain

Introducing Methods Results Conclusion

**Results**

ICP: 0 mmHg

**Linear-Elastic**  **Poroelastic**

<table>
<thead>
<tr>
<th></th>
<th>Linear-Elastic</th>
<th>Mean Strain</th>
<th>Poroelastic</th>
<th>Mean Strain</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamina Cribrosa</td>
<td>1.64%</td>
<td>1.5%</td>
<td>2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optic Nerve</td>
<td>1%</td>
<td>1.4%</td>
<td>10.4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First Principal Strain

ICP: 30 mmHg

<table>
<thead>
<tr>
<th>Shift</th>
<th>Linear-Elastic</th>
<th>Poroelastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Difference</td>
<td>2.4%</td>
<td>16.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Linear-Elastic Mean Strain</th>
<th>Poroelastic Mean Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamina Cribrosa</td>
<td>1.5%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Optic Nerve</td>
<td>1.3%</td>
<td>2.1%</td>
</tr>
</tbody>
</table>
**Results**

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Linear-Elastic Mean Strain</th>
<th>Poroelastic Mean Strain</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamina Cribrosa</td>
<td>-2.8%</td>
<td>-0.05%</td>
<td>24.5%</td>
</tr>
<tr>
<td>Optic Nerve</td>
<td>-1.7%</td>
<td>-1.0%</td>
<td>11.1%</td>
</tr>
</tbody>
</table>

ICP: 0 mmHg
### Results

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Linear-Elastic Mean Strain</th>
<th>Poroelastic Mean Strain</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamina Cribrosa</td>
<td>-2.6%</td>
<td>-0.3%</td>
<td>22.2%</td>
</tr>
<tr>
<td>Optic Nerve</td>
<td>-1.6%</td>
<td>-0.44%</td>
<td>18.2%</td>
</tr>
</tbody>
</table>

ICP: 30 mmHg
Conclusions

• We observed large differences in the strains between the linear-elastic and poroelastic model simulations.

• Poroelastic models may be more physiologically relevant because they can apply fluid pressures and allow fluid flow within tissues.
  – However, we need more information on the permeability of ocular structures to implement more accurate FE models.
Acknowlegements

• DeVon Griffin