Supplementary Materials

The Impact of Choroidal Swelling on Optic Nerve Head Deformation

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Donnan Equilbrium Swelling

This material model allows volumetric change (i.e. swelling or shrinking) of a tissue by achieving equilibrium of charged particles between the tissue and an external bath. These equations typically govern effects associated with osmotic gradients, but have been adopted here as a simple modeling artifice to represent volume changes in tissues within the FEBio simulation code. In short, the Cauchy stress within the choroid is described as:

\[ \sigma = -R \times T \times \left( \sqrt{(c^F)^2 + (\bar{c}^*)^2} - \bar{c}^* \right) + \sigma^e \]  

where \( R \) is the ideal gas constant (8.314 J / mol K), \( T \) is body temperature (37°C expressed in Kelvin), and \( \bar{c}^* \) represents the external bath osmolality, assumed to be the osmolality of typical biological tissues (300 mOsm). \( \sigma^e \) represents the stress from the solid matrix of the choroid. Here, we assumed the choroid to be represented as a linear-elastic material with a Young’s modulus (E) of 0.3 MPa, which is the same value adapted for the central retinal vessel. \( c^F \) represents the fixed-charge density of the current configuration compared to the reference configuration and is a function of \( c_0^F \).

\[ c^F = \frac{\varphi}{J^{-1} + \varphi} \times c_0^F \]

\( \varphi \) represents the gel porosity and ranges from 0 to 1, and was chosen to be 0.10. \( J \) represents the relative volume (e.g. the Jacobian of the deformation gradient matrix). In this equation \( c_0^F \) drives the fixed-charged density and has units of milliequivalent per liter (mEq/L). In our simulations, changes in \( c^F \) cause changes in the volume of the choroid. Thus, the use of Donnan equilibrium swelling was a convenient vehicle that allowed us to apply a prescribed amount of volume change, i.e. swelling, by changing a single coefficient (\( c_0^F \)). Specifically, setting \( c_0^F = 0 \) mEq/L corresponded to 0 uL of choroidal swelling while \( c_0^F = 95 \) mEq/L corresponded to a 14.2 uL change in choroidal volume for these geometries. It is important to note that we based the values of \( c_0^F \) directly on the volume change occurring in the choroid, and we do not claim that choroidal swelling in the eye occurs due to Donnan effects.
Abbreviations:

AR – annular ring
BM – Bruch’s Membrane
CRV – central retinal vessel
ΔV – choroidal volume change
Dura – dura mater
E- Young’s Modulus
IIH – idiopathic intracranial hypertension
ICP – intracranial pressure
IOP – intraocular pressure
LC – lamina cribrosa
LHS – Latin hypercube sampling
MAP – mean arterial pressure
NAION – nonarteritic anterior ischemic optic neuropathy
uL – microliters
ON – Optic Nerve
ONH – optic nerve head
PRCC – Partial Rank Correlation Coefficient
ppSC – peripapillary sclera
Pia – pia mater
PLNT – prelaminar neural tissue
PS – principal strain
RGC – retinal ganglion cells
RLNT – retrolaminar neural tissue
SC – sclera
SANS – space flight-associated neuro-ocular syndrome
v - Poisson ratio