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Modeling the consolidation of a cylindrical poroelastic composite and application to the optic nerve

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The mechanical behavior of the optic nerve is largely unknown but is of critical importance to understanding injury and subsequent visual dysfunction from mechanical trauma or elevated intracranial (brain) pressure. The structure of the optic nerve resembles a cylindrical composite with an outer elastic layer and an inner biofluid-saturated porous core. Current computational and material models do not fully capture the complexities of this tissue's structure, particularly the biofluid has not yet been considered as a load-supporting material.

We developed an analytical model for a cylindrical composite using the theory of poroelasticity. We determined how the solid deformation of the composite is coupled to fluid flow, based on the model of poroelastic soil consolidation by initially developed by Karl von Terzaghi. The expression for the consolidation constant for the composite cylinder was found. We systematically investigated how variations in the geometry and material properties of the outer layer and the inner core of the composite affect the consolidation constant, and therefore the fluid flow, stress, and deformation. The consolidation process of the cylindrical composite depends on the radius of the outer and inner cylinders and their material properties. Sets of parameters can be found where the outer cylinder does not affect the consolidation process of the inner, poroelastic, core. However, these parameters are not appropriate for the optic nerve. Therefore, the outer layer of the optic nerve significantly affects the fluid flow and consolidation behavior of this tissue and has implications for clinical models.

We also modeled uniaxial tension or compression of this cylindrical composite in the absence of fluid draining—when the composite cylinder is sealed. Here, the internal stress is distributed between the layer surrounding the optic nerve, the solid skeleton of the core, and the fluid. Literature values for the magnitude of the compressive or tensile stress were applied to the optic nerve. The results show that the fluid pressure in this tissue can be as large as one third of the applied stress and as high as 120Pa (0.017psi). This magnitude may be significant to injure the nerve. The work stimulates future investigations into the role of fluid pressure during deformation of the optic nerve. The model also provides a framework for experimentally measuring material properties of composite biomaterials subjected to uniaxial tension or compression. We are currently validating the analytical model against creep experiments of pig and cow optic nerves. Our preliminary findings show that the creep behavior can be modeled as consolidation of the composite cylinder, therefore more specimens will be tested.

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References

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