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Dual-porosity poroviscoelasticity and quantitative hydromechanical characterization of the brain tissue with experimental hydrocephalus data

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HIGHLIGHTS

- A time-dependent, dual-porosity poroviscoelastic model of the brain is suggested.
- The model is used to assess the results of perfusion test on animal models.
- The brain tissue permeability and shear modulus are estimated.
- The filtration coefficient of the brain capillaries is estimated.
- The optimized model accurately predicts the measured data of perfusion test.

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ABSTRACT

Hydromechanical brain models often involve constitutive relations which must account for soft tissue deformation and creep, together with the interstitial fluid movement and exchange through capillaries. The interaction of rather unknown mechanisms which produce, absorb, and circulate the cerebrospinal fluid within the central nervous system can further add to their complexity. Once proper models for these phenomena or processes are selected, estimation of the associated parameters could be even more challenging.

This paper presents the results of a consistent, coupled poroviscoelastic modeling and characterization of the brain tissue as a dual-porosity system. The model draws from Biot's theory of poroviscoelasticity, and adopts the generalized Kelvin's rheological description of the viscoelastic tissue behavior. While the interstitial space serves as the primary porosity through which the bulk flow of the interstitial fluid occurs, a secondary porosity network comprising the capillaries and venous system allows for its partial absorption into the blood. The correspondence principle is used in deriving a time-dependent analytical solution to the proposed model. It allows for identical poroelastic formulation of the original poroviscoelastic problem in the Laplace transform space.

Hydrocephalus generally refers to a class of medical conditions which share the ventricles enlargement as a common feature. A set of published data from induced hydrocephalus and follow-up perfusion of cats' brains is used for quantitative characterization of the proposed model. A selected portion of these data including the ventricular volume and rate of fluid absorption from the perfused brain, together with the forward model solution, is utilized via an inverse problem technique to find proper estimations of the model parameters. Results show significant improvement in model predictions of the experimental data.

The convoluted and coupled solution results are presented through the time-dependent plots of the ventricular volume undergoing the perfusion experiment. The plots demonstrate the intricate interplay

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of viscous and poroelastic diffusive time scales, and their competition in reaching the steady state response of the system.

1. Introduction

Constitutive models of the brain tissue are usually selected based on the type and range of the strain rates associated with its particular pathological or normal conditions. Since the pioneering publication of Hakim (1976), in which the brain was described as a "*porous, sponge-like viscoelastic material,*" viscoelasticity and poroelasticity have been commonly used for this purpose (Kyriacou et al., 2002; Miller, 2011). Poroelastic models (Biot 1941, 1956a) are accepted to be compatible with processes which involve low-strain-rate deformations of the brain, such as infusion, edema, hydrocephalus, and hemorrhage (Nagashima et al. 1987; Kaczmarek et al., 1997; Kyriacou et al., 2002; Owler et al., 2004; Smillie et al., 2005; Wirth and Sobey, 2009; Tully and Ventikos, 2011; Sobey et al., 2012). The landmark work of Franceschini et al. (2006) shed light on the consolidation-type behavior of the brain tissue after investigation of the oedometer test, an experiment which was originally designed and carried out in studies related to soil mechanics. The results revealed that while consolidation (deformation of solid matrix due to pore fluid flow and its drainage from the interstitial space) is the leading mechanism in quasi-static deformation of the brain tissue, the addition of a viscous component to its rheological model is necessary in achieving complete adherence between the experimental data and theoretical formulations. This finding has recently been confirmed using force-controlled indentation of the brain tissue in living animals, and after observing its progressive deformations under small loadings (Shulyakov et al., 2011, 2012).

The classical hypothesis of cerebrospinal fluid (CSF) circulation suggests that the arachnoid granulations surrounding the venous system of dura are its primary absorption sites. A comprehensive review by Kapoor et al. (2008) describes in detail the structure of the arachnoid granulations and the CSF absorption mechanisms. In particular, using the human arachnoid granulation cells grown on a filter membrane, Grzybowski et al. (2006) provided an in-vitro model, which allowed for quantification of its directional hydraulic conductivities. Existence of alternate mechanisms for CSF outflow is also suggested. The role of extracranial lymphatic vessels in CSF absorption and their connection with subarachnoid space was studied by Johnston (2003) and Koh et al. (2006). More recent studies have brought in evidence the para-arterial influx of subarachnoid CSF into the cortex, followed by the interstitial fluid clearance throughout the parenchyma (Iliff et al., 2012). The real-time monitoring of live mice brains via two-photon imaging has demonstrated the critical role that this transport of fluid and solutes, currently known as glymphatic system, plays in the clearance of neurotoxic waste from the brain during sleep (Xie et al., 2013).

The earlier investigations of Greitz (1992) and Greitz et al. (1994) through magnetic resonance imaging and radionuclide cisternography suggested that the absorption of the CSF also occurs via the paravascular and interstitial spaces of the central nervous system. This would especially be the case where the natural pathways of CSF flow are obstructed, as for instance in non-communicating hydrocephalus. Hydrocephalus is generally referred to a class of medical conditions which share the enlargement of the ventricles as a common feature (Bouzerar et al., 2012). While the interstitial fluid drains into the ventricles in normal cases, the CSF flow in the cases of hydrocephalic brain might reverse towards the parenchyma (Hochwald et al., 1969; Bloch et al., 2006), where it can be absorbed by microvessels (Sahar et al. 1969a, 1969b). Traces of the radiolabeled perfusate or dye fluid in the blood of hydrocephalic animal models (Strecker et al., 1973) indicate the likelihood of such existing mechanisms. In a more direct observation, the silicone oil-induced hydrocephalus experiments of Del Bigio and Bruni (1987) reported an increase in the specific gravity of the white matter in the corpus callosum of rabbits. The increase concurred with significant water loss throughout the entire cerebrum, except at the ventricular surface. Lux et al. (1970) examined biopsies from the brain's parietal lobe of animals with induced hydrocephalus. Likewise, they reported narrow regions of periventricular tissue with significantly high water content. A similar observation was also made via in-vivo magnetic resonance imaging of hydrocephalic animal brain (Deo-Narine et al., 1994). These observations indicate the significant role of parenchyma and its network of capillaries in regulating the CSF circulation within the central nervous system (Hochwald et al., 1972; Levine, 1999; Bloch et al., 2006, Orešković and Klarica, 2011).

In view of these facts and observations, a hydromechanical continuum model suitable for theoretical analysis of the brain tissue is presented in Fig. 1. It comprises the following components. The brain is considered as a porous, viscoelastic time-dependent behavior with its associated mechanical moduli. Its porous structure allows for the interstitial fluid movement to be driven by the existing or induced pressure gradients. The model assumes that this transport follows Darcy's law of fluid flow through saturated porous media. The notation κ represents the brain hydraulic conductivity, i.e., the ratio of permeability, k, to pore fluid viscosity, μ. The suggested model is theoretically compatible with Biot's theory and is generalized to account for the viscoelastic deformation of the brain tissue. Such generalization was formerly developed by Biot (1956b), and later nurtured through the principle of correspondence between poroelasticity and poroviscoelasticity (Taylor and Aifantis, 1982; Abousleiman et al., 1993; Coussy, 1995; Hoang and Abousleiman, 2012). The time-dependency of mechanical properties is a well-known feature of soft tissue (Humphrey, 2003). A generalized Kelvin's model is herein selected to describe the viscoelastic rheology of the brain. Its conceptual representation is shown in Fig. 1, with an arrangement of springs and a damper, in such a way that under a constant uniaxial stress its Young's modulus varies exponentially between the initial and final values, $E(0^+)=E_1$, and $E(\infty)=(E_1E_2/E_1+E_2)$.

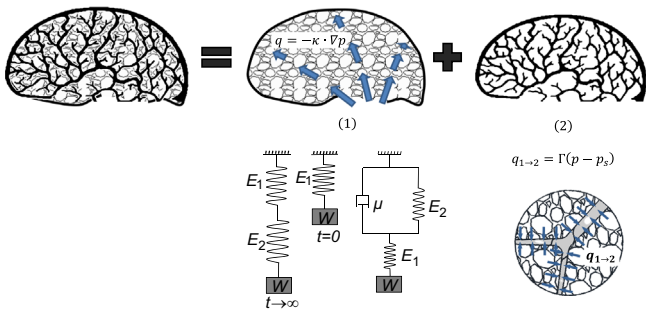

Fig. 1. Dual-porosity poroviscoelastic model of the brain comprising the following components: (1) the porous, fluid saturated and viscoelastic tissue with the generalized Kelvin's rheological parameterization of moduli E_1 and E_2, as well as damping parameter μ. (2) A continuum network of microvessls, which provides a distributed fluid sink for the interstitial fluid.