A realistic model of brain tissue in case of hydrocephalus: application of MRI, DTI and MRE

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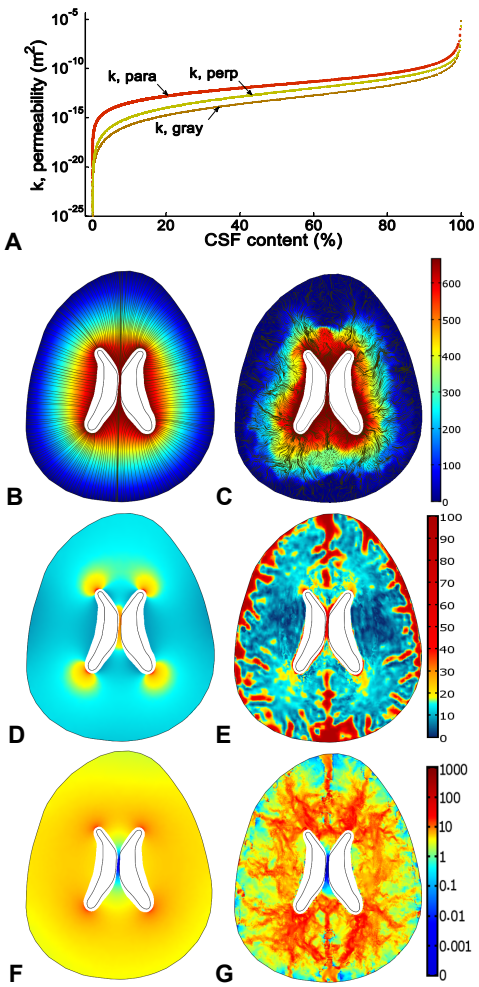
Introduction: Hydrocephalus is a disorder of the brain associated with a flow disruption of the cerebrospinal fluid (CSF) [1]. The present study combines the results of three non-invasive imaging techniques MRI, DTI and MRE together with a FE model. The simulation aims to understand how important the non-homogeneous and non-isotropic permeability and elasticity properties are in the case of hydrocephalus; more specifically, in the transmission of the low transmantle pressure within parenchyma [2]. Using advantageous of these MRI-based methods, a simple but realistic model of brain is also presented.

Methods: A numerical slice model of one given brain is built in a finite element (FE) software [3]. The geometries of the ventricles and the skull delineating the brain parenchyma in a horizontal section are obtained by MRI. Due to the existence of bundles of axons, permeability and elasticity stiffness are higher along the fiber tracts (white matter), whereas regions such as grey matter are much more isotropic. Mechanically speaking, the brain parenchyma is modeled as a porous medium fully saturated with the cerebrospinal fluid (CSF) using the Biot's theory of consolidation [4]. Direction of axon bundles is determined using DTI method [5]. As mean diffusivity (MD) [m^2/s] allows distinguishing between cerebrospinal fluid content and brain tissue, novel ideas are introduced to link the white and gray matter permeabilities with MD in brain parenchyma. Anisotropic MRE is used to determine the shear properties in the same local frame [6]. Two assumptions are considered to relate the data coming from MRE to DTI ones. The elasticity (MRE) has the same eigen frame as permeability and diffusivity (DTI) and diffusive fraction of anisotropy behaves the same as mechanical fraction of anisotropy. Under an applied transmantle pressure, we seek the influence of the anisotropy and inhomogeneity of both permeability and elasticity throughout the brain parenchyma. Two models, Isotropic (Iso) and Transverse Isotropic (TI), are tested to study these influences on the CSF flow created by the imposed pressure gradient.

Results: The proposed permeability coefficients for gray and white matter based on the formulas from literature and a link with MD are presented in Fig.A. For the average CSF content of 18% within parenchyma, the permeability values are in a similar range as reported in the literature [7,8,9]. Fig.B,C show the ventricle dilation, the CSF pressure and the CSF streamlines under the imposed pressure gradient in both cases. The fluid flow and pressure distribution, contrary to their smooth pattern in Iso model (Fig.B), are highly distorted by anisotropy and inhomogeneity of both permeability and elasticity as shown in Fig.C. The pressure field is affected by the anisotropy and inhomogeneity of the parenchyma (Fig.C). It drops when the CSF content increases, as can be seen in the pathways between two hemispheres (Fig.C). Fig.D,E show the final fluid content for both cases. The fluid content at the ventricles horns and in the region surrounded by the two ventricles shows a marked increase from the initial value (the red region in Fig.D,E). The high amount of fluid content in the red regions on the ventricles horns is generally accepted as the reason for periventricular lucency (PVL) [1]. The high discharge of CSF on the ventricles horns in Iso model (Fig.D) comes from the geometrical effect while such effects in TI model is associated with the CSF dependent permeability and elasticity (Fig.E). Fig.F,G present the CSF velocity plot in Iso and TI models. Comparing with Iso model (Fig.F), introducing these parameters in TI model, yields the wider range of CSF velocity (Fig.G). The maximum fluid velocity appears in TI model where both the permeability and elasticity matrices are inhomogeneous and anisotropic. Introducing these parameters yields the same CSF velocity range as reported in the literature (Fig.G) [7]. Contrary to the smooth pattern of fluid velocity in Iso model (Fig.F), CSF pathways are developed in TI model (Fig.G). The displacements on the horns and the line separating the ventricles are not influenced by the anisotropy and inhomogeneity of parenchyma, while the section of ventricle behind the corona radiata dilates much more in TI model.



A) Proposed CSF dependent permeability values of gray and white matter. Pressure (Pa) and streamlines of fluid in **B)** Isotropic and **C)** TI models. Final CSF content (%) in **D)** Isotropic and **E)** TI models. Fluid velocity magnitude (μm/sec) in **F)** Isotropic and **G)** TI models.

Discussion: The computed results clearly show the importance of such anisotropic and inhomogeneity in permeability and elasticity properties notably in the CSF velocity field. The transmission of the applied pressure gradient is substantially influenced by introducing these parameters in permeability and elasticity. It appears also that the inhomogeneity plays the more important role than anisotropy. The importance of both parameters is also demonstrated in the ventricle dilation and in the flow field by developing CSF pathways. The CSF velocity field becomes much more inhomogeneous, as observed experimentally. With the space dependent CSF content and TI permeability and elasticity, the proposed model becomes much more realistic.

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