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LETTER TO THE EDITORS

Computational modelling of hydrocephalus

Dear Dr. Guilak

We refer to the recent paper (Lefever et al., 2013) recently published in Journal of Biomechanics. This paper presents finite element simulation of the development of non-communicating hydrocephalus and uses results of our paper (Dutta-Roy et al., 2008), also published in Journal of Biomechanics, for comparisons.

In Dutta-Roy et al. (2008) we consider Normal Pressure Hydrocephalus (NPH) that is a type of communicating hydrocephalus and not the non-communicated hydrocephalus. The difference goes far beyond semantics: in Normal Pressure Hydrocephalus elevated ventricular pressure is not observed and still ventricles become very large.

In Dutta-Roy et al. (2008) we argue that because of extremely slow loading rates during the development of hydrocephalus it is the slow strain-rate behaviour of the solid phase that governs the deformation response of the biphasic continuum. Therefore the value used for initial permeability and the model relating the permeability to changing void ratio and strain have minimal influence on model response. This fact is explicitly demonstrated in Fig. 4 in Dutta-Roy et al. (2008) that we reproduce in Fig. 1.

The large ventricular volume enlargement, reported in Lefever et al. (2013) appears to be solely due to the assumption, alluded to by the authors in the Discussion, that tissues present between the brain and the skull are able to collapse to zero volume and therefore create space for the brain to expand into. This assumption is unreasonable and in conflict with current knowledge of brain anatomy (Haines et al., 1993) and biomechanics (Miller, 2011; Bilston, 2011), as is clear from Fig. 2.

Moreover, it has been measured using MRI-based techniques that the volume of subarachnoid cerebrospinal fluid space is not different in patients suffering from normal pressure hydrocephalus (NPH) from that in the control group (Matsumae et al., 1996). Therefore collapse of this space in no way can be responsible for brain expansion and ventricular enlargement.

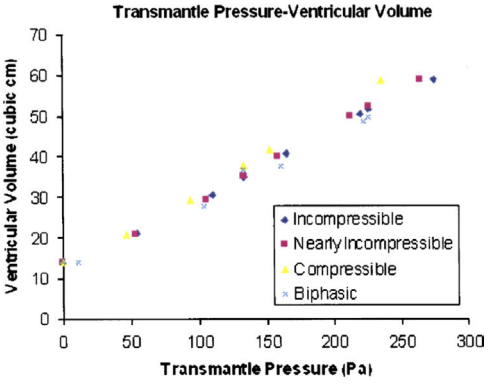

Fig. 1. Transmantle pressure difference vs. ventricular volume for single phase (incompressible, nearly incompressible and compressible) and biphasic brain model (Dutta-Roy et al., 2008).

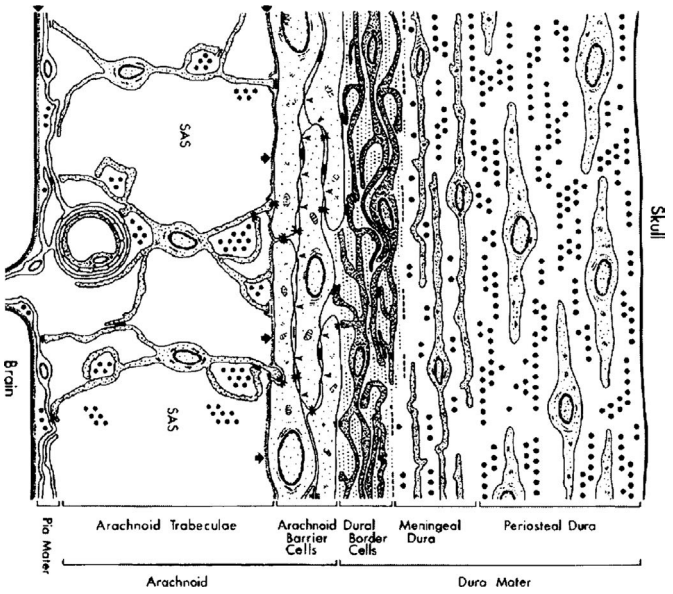

Fig. 2. Structure of the brain–skull interface (Miller et al., 2010), adapted from Haines et al. (1993).

We believe that results presented in Lefever et al. (2013) in no way undermine the main conclusion of Dutta-Roy et al. (2008) that the hypothesis of a purely mechanical basis for NPH growth needs to be revised.

We would like to respectfully request that this letter is published in the Journal.

Yours sincerely,
K.M., S.B., A.W.

Conflict of interest

We declare that we do not have any conflict of interest with regard to this Letter to Editor.

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Reply to letter to the editor: "Computational Modelling of Hydrocephalus"

We appreciate the interest that Prof. Miller and colleagues have taken in our recent computational study of noncommunicating hydrocephalus (Lefever et al., 2013).

We agree with Prof. Miller and his colleagues that classification of the different types of hydrocephalus goes beyond semantics. Classically, hydrocephalus is categorized based on state of the Sylvius aqueduct that connects the lateral and third ventricles to the fourth ventricle (Corns and Martin, 2012). In communicating hydrocephalus, the aqueduct is unobstructed and the cerebrospinal fluid produced in the lateral ventricles can flow freely to the fourth ventricle via the aqueduct. In contrast, in noncommunicating hydrocephalus, the aqueduct is obstructed or collapsed, such as by a tumor growing adjacent to it, and the cerebrospinal fluid cannot flow freely to the fourth ventricle via the aqueduct. While the Sylvius aqueduct does not appear to be explicitly represented in the geometry used by Dutta-Roy et al. (2008) and flow through it was not accounted for in their model, Prof. Miller and colleagues consider their model to be of communicating hydrocephalus. In contrast, while our model similarly does not include the Sylvius aqueduct, we consider it to represent noncommunicating hydrocephalus.

We also agree with Prof. Miller and his colleagues that the space between the cerebrum and the brain has a very complex structure, as illustrated in Fig. 2 of their letter. This complexity causes computational challenges, specifically in representing this structure within the geometry and mesh, and in applying an appropriate boundary condition. Although there is experimental evidence that this space does, at least, partially collapse (Milhorat and Clark, 1970; Milhorat et al., 1970, 1971), many recent models of hydrocephalus have assumed the outer surface of the brain to be fixed (Cheng and Bilston, 2010; García and Smith, 2010; Levine, 2008; Momjian and Bichsel, 2008; Shahim et al., 2010, 2012; Tully and Ventikos, 2009, 2011; Wilkie et al., 2012), in essence assuming either that the structures within the subarachnoid space are significantly stiffer than the cerebrum or that the subarachnoid space is sufficiently thin such that the rigid skull is in direct contact with the brain. In contrast, Mehrabian and Abousleiman (2011) represented the trabeculae within the subarachnoid space as springs that resist deformation of the cerebrum, but they acknowledge that there is a lack of experimental data for the stiffness of the trabeculae.

Motivated by the experimental evidence of Milhorat and colleagues, but without an experimentally measured value for the stiffness of the trabeculae, in Lefever et al. (2013), we adopted a simplistic approach, representing the subarachnoid space as a gap between the cerebrum and the anatomically reconstructed skull, and allowing the cerebrum to deform until contact with skull, effectively collapsing that space. We acknowledged this as a limitation of our study in the Discussion section of our paper, and our research group is currently exploring alternative representations of this region and corresponding boundary conditions (Hendra, 2013). However, it is important to note that Prof. Miller and colleagues utilized a nearly identical approach, modeling the subarachnoid space as a "3 mm gap between the brain outer surface and the skull" (Dutta-Roy et al., 2008, Section 2.4). Furthermore, they "used a frictionless, finite sliding, node-to-surface penalty contact between the brain and the skull." Hence, the criticism in their letter seems to apply to their own study, as it appears that Dutta-Roy et al. (2008) also allow this space to

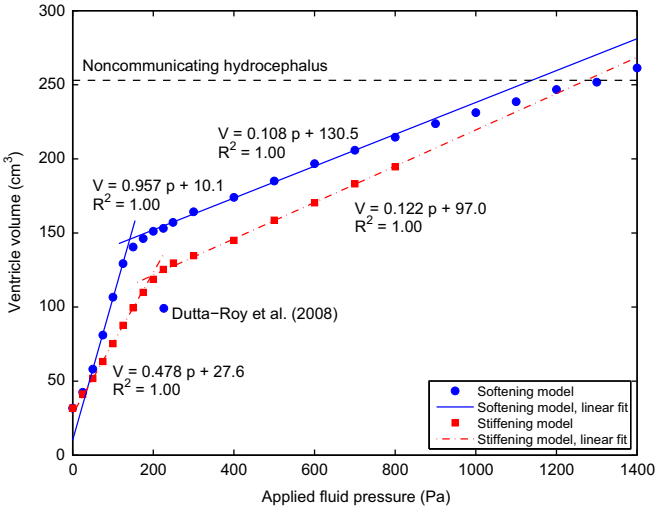

Fig. 1. Maximum ventricle volume at several applied fluid pressures for the two sets of nonlinear strain energy function parameters and variable hydraulic conductivity with deformation ($M=1$). The horizontal dashed line indicates the volumetric criteria for noncommunicating hydrocephalus. The transition between the linear trends is associated with the contact of the cerebrum with the skull (Lefever et al., 2013, Fig. 4).