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Research Paper

Transient solid–fluid interactions in rat brain tissue under combined translational shear and fixed compression

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ABSTRACT

An external mechanical insult to the brain may create internal deformation waves, which have shear and longitudinal components that induce combined shear and compression of the brain tissue. To isolate such interactions and to investigate the role of the extracellular fluid (ECF) in the transient mechanical response, translational shear stretch up to 1.25 under either 0 or 33% fixed normal compression is applied without preconditioning to heterogeneous sagittal slices which are nearly the full length of the rat brain cerebrum.

The normal stress contribution is estimated by separate unconfined compression stress–stretch curves at 0.0667/s and 1/s engineering strain rates to 33% strain. Unconfined compression deformation causes lateral dimension expansion less than that predicted for an incompressible material under large deformation and often a visible loss of internal fluid from the specimen so that the bulk brain tissue is not incompressible in vitro, as sometimes assumed for mathematical modeling.

The response to both slow 0.001/s and moderate 1/s shear translational stretch rates is deformation rate dependent and hardening under no compression but under 33% compression is nearly linear perhaps because of increased solid–solid friction. Both shear and normal stress relaxation are faster after the fast rate deformation possibly because higher deformation rates produce higher ECF hydrostatic pressure that primarily drives stress relaxation.

The experimental results on ECF behavior guide the form of our nonlinear viscoelastic mathematical model. Our data are closely fit by non-equilibrium evolution equations that involve at most three specimen-specific empirical parameters and that are based on the idea that stretch of axons and glial processes resists load-induced ECF pressure.

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1. Introduction

Brain tissue, when exposed to external mechanical insults or neurosurgery, may be subjected to internal deformation waves composed of longitudinal and shear components that induce combined translational shear and compression deformations. While compression and translational shear have been studied separately in published experiments, the interaction of compressive and translational shear deformations has not previously been reported.

Brain tissue is a biphasic material since it is composed of solid matter as well as intracellular and extracellular fluid (ECF), but the role of the ECF in the mechanical response of brain tissue has been neglected in many studies. The ECF surrounds brain cells and lies in the extracellular space comprising about 20% of the brain parenchymal volume and is the medium for diffusion-based functions such as nutrient transport to, and waste removal from, the cells and non-synaptic cell–cell communication (e.g. Verkman, 2013). Confined compression tests of rat brain tissue (Haslach et al., 2014) provide evidence of the mechanical interaction of the ECF with the solid matter in brain tissue and lead to the hypothesis that one immediate mechanical cause of tissue damage under an external mechanical insult is increased hydrostatic pressure in, and pathological flow of, the ECF. The ECF is a candidate for the medium through which deformations from external insults are transmitted to deeper brain regions. Evidence on the role of the ECF in the mechanical response of rat brain tissue to slow and moderate combined shear and compression deformation could therefore lay a foundation for future studies of brain damage caused by such combined deformations.

The two types of reported shear tests are torsional which generate shear by a rotational contact on the specimen surface (e.g. Bilston et al., 2001; Hrapko et al., 2006, 2008) and translational (e.g. Rashid et al., 2013), which apply a linear deformation to the surface. Translational shear tests without compression have applied small strain sinusoidal loading (Arbogast et al., 1997; Nicolle et al., 2004) and large deformation, constant rate deformations followed by stress relaxation (Darvish and Crandall, 2001; Prange and Margulies, 2002; Ning et al., 2006). Torsional shear tests may not relate to the shear caused by a wave inside the brain because the shear wave component induces translational shear in vivo rather than rotational shear. The models proposed in these works require at least six empirical coefficients to qualitatively fit their data.

To measure the influence of the ECF on the mechanical response under large deformation, we conduct translational shear tests after the application of unconfined compression on specimens that are large enough to allow ECF redistribution during the deformation. Our hypothesis is that the role of the ECF is represented by variations in the shear stress supported under different combinations of shear and compression. The experimental results are closely fit by novel evolution differential equations requiring at most three empirical coefficients.

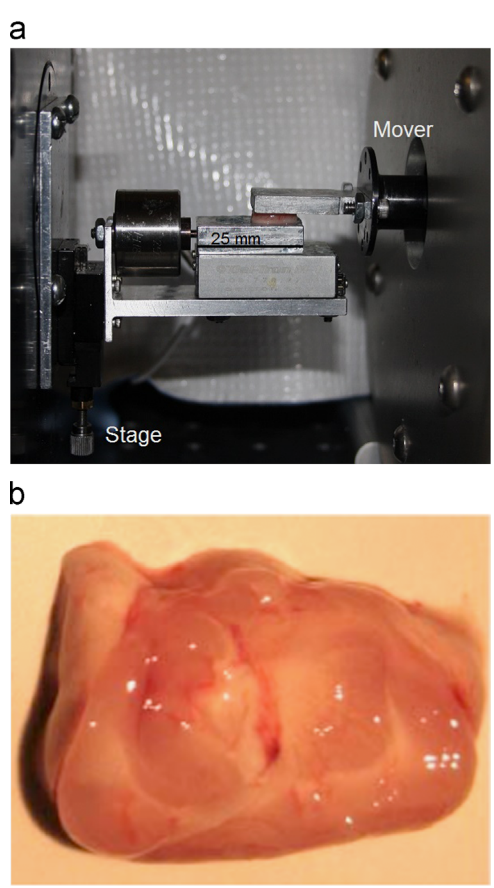

Fig. 1 – (a) The fixture for combined shear and compression. The stage allows adjusting the magnitude of compression prior to shear. (b) Heterogeneous specimen from the full sagittal slice of the rat brain cerebrum.

2. Method and materials

To investigate the influence of ECF on the mechanical response under shear and compression, we use large, heterogeneous slices of brain tissue. Our specimens are nearly the length of the cerebrum and contain multiple regions of the brain. Therefore, the mechanical response closely approximates that of the full rat brain and includes interactions among different regions, and the specimen allows room for ECF redistribution. In contrast, many studies choose specimens from a particular brain region of a larger mammal such as a pig, sheep or cow (e.g. Rashid et al., 2013; Hrapko et al., 2008; Miller and Chinzei, 2002; Prange and Margulies, 2002). Others have also used the indenter technique, which would not apply force to a large enough region to include the ECF response whether in vivo or in vitro (e.g. Shafieian et al., 2009; Gefen et al., 2003) .

A shear fixture (Fig. 1a) to accommodate such specimens was designed and built to apply translational shear from 25 mm long flat grips to flat rectangular plate specimens excised from the rat brain. The top plate is attached to the test machine mover. For support, the bottom plate rests on a linear bearing (Del-tron M-1 linear ball slide) with manufacturer specified 0.003 coefficient of friction. A 250 g load cell (Interface WMCP-250G-567) attached to the bottom plate measures the reaction force. A stage (ThorLabs T12X) permits