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Viscoelastic parameter identification of human brain tissue

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Abstract

Understanding the constitutive behavior of the human brain is critical to interpret the physical environment during neurodevelopment, neurosurgery, and neurodegeneration. A wide variety of constitutive models has been proposed to characterize the brain at different temporal and spatial scales. Yet, their model parameters are typically calibrated with a single loading mode and fail to predict the behavior under arbitrary loading conditions. Here we used a finite viscoelastic Ogden model with six material parameters–an elastic stiffness, two viscoelastic stiffnesses, a nonlinearity parameter, and two viscous time constants–to model the characteristic nonlinearity, conditioning, hysteresis and tension-compression asymmetry of the human brain. We calibrated the model under shear, shear relaxation, compression, compression relaxation, and tension for four different regions of the human brain, the cortex, basal ganglia, corona radiata, and corpus callosum. Strikingly, unconditioned gray matter with 0.36 kPa and white matter with 0.35 kPa were equally stiff, whereas conditioned gray matter with 0.52 kPa was three times stiffer than white matter with 0.18 kPa. While both unconditioned viscous time constants were larger in gray than in white matter, both conditioned constants were smaller. These rheological differences suggest a different porosity between both tissues and explain–at least in part–the ongoing controversy between reported stiffness differences in gray and white matter. Our unconditioned and conditioned parameter sets are readily available for finite element simulations with commercial software packages that feature Ogden type models at finite deformations. As such, our results have direct implications on improving the accuracy of human brain simulations in health and disease.

Keywords: Human brain; Rheological testing; Finite viscoelasticity; Ogden model; Parameter identification

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1. Introduction

Understanding the mechanical characteristics of human brain tissue has challenged scientists for many decades. The ultrasoft behavior is highly sensitive to spatial and temporal resolutions [1]. Even for quasi-static loading rates and relatively small strains, brain tissue exhibits a highly nonlinear, hysteretic behavior [2, 3, 4], where both time-independent and time-dependent characteristics show regional variations [5, 6, 4, 7]. A key to establish realistic constitutive models for the brain is not only to develop mathematical models that capture the time-dependent tissue response at finite strains but also to design appropriate experiments to accurately identify the corresponding material parameters.

Limited by the availability of human brain tissue [8, 9, 10, 11, 6], researchers alternatively consulted porcine [12, 13, 14] or bovine brains [15, 16, 17, 18] due to their structural similarities with the human brain. Animal studies have been exceptionally valuable to better understand the highly complex mechanical response of brain tissue. However, to accurately characterize, model, and simulate the human brain, data from a different species could provide imprecise results [13].

Previous studies concerned with the time-dependent mechanical behavior of human brain tissue have mostly been limited to linear viscoelastic properties at small strains [8, 9, 10, 11, 6]. A popular approach to characterize the time-dependent behavior using a Prony series [12, 13, 14, 18, 6], has recently resulted in poor predictions of porcine brain experiments when the actual strain history was taken into account [19]. Since material parameters identified for a single loading mode do not necessarily represent the constitutive behavior under arbitrary loading cases [12, 2], we are generally limited by the lack of experimental data for accurate parameter identification [20]. Here, we use the experimental data of human brain tissue under multiple uniaxial loading conditions, cyclic simple shear, unconfined compression, tension, and shear relaxation, and compression relaxation, for four different brain regions, the cortex, the basal ganglia, the corona radiata, and the corpus callosum. To eliminate inter-specimen variations, we performed all five tests sequentially on one and the same specimen. In one region, the corona radiata, we performed additional multiaxial tests [4], combined compression/tension-shear loading, to provide viscoelastic material parameters that are capable of predicting the response of human brain tissue under multiaxial loading conditions. The objective of this study was to systematically compare the viscoelastic response of human brain tissue for five different types of loading and, ultimately, identify a set of material parameters

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