Characterisation of Porcine Brain Tissue Mechanical Properties at Large Deformations

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I. INTRODUCTION

The lack of treatment options for traumatic brain injury (TBI) motivates the study of the biomechanics of injury and brain tissue to improve prevention and protection strategies. Finite element (FE) models have been developed to predict the brain tissue's mechanical response to TBI and injury-risk [1]. A comprehensive characterisation of the brain's mechanical properties is essential for these computational models to predict a biofidelic response. Studies have shown that brain tissue is a viscoelastic material exhibiting anisotropic behaviour [2]. Due to ethical concerns, porcine brain models are advantageous in mechanical studies due to its similarity to human brain tissue in neuroanatomy and size [3]. Our previous findings identified various regional differences in the shear moduli of porcine brain tissue within the coronal [4], sagittal, and horizontal planes at 10% strain. We also found that the shear moduli of the cortex white matter and thalamus slices excised in the coronal plane were significantly different compared to that in the horizontal plane. The current study extends this analysis to larger deformations, up to 30% strain.

II. METHODS

Brain tissue samples were extracted from euthanised pigs and transported in ice cold oxygenated artificial cerebrospinal fluid (aCSF) supplemented with glucose. Tissue slices were cut in the coronal, sagittal, and horizontal planes. Indentation testing was conducted using a custom designed microindentation device [4-5] within three hours postmortem. Each tissue sample was adhered to a dish and placed on a 10 g load cell (GSO-10, Transducer Techniques, Temecula, USA). Samples were maintained in CO_2 independent medium supplemented with 4 mg/mL glucose at physiological pH. The indentation was made using a 250 μm radius flat ended cylindrical punch (National Jet Company, Cumberland, USA) mounted to a linear actuator (M-227.10, Physik Instrumente, Karlsruhe, Germany), which was connected to a capacitive sensor to monitor displacement (capaNCDT 6100, Micro Epsilon, Ortenburg, Germany). Multistep indentation depths of 40, 80, and 120 μm were achieved, corresponding to nominal strains of 10, 20, and 30%. A custom LabVIEW code (LabVIEW 8.6, National Instruments, Austin, USA) was used to collect the displacement and load histories. Multiple indentation tests were conducted within each anatomical region of each tissue slice.

The quasilinear theory of viscoelasticity (QLV) was used to model the nonlinear behaviour with the following expression,

$$P(t) = \frac{4R\kappa}{1-\nu}\int_0^t G(t-\tau)\left(\frac{\partial T^e}{\partial \delta}\right)\left(\frac{d\delta}{d\tau}\right)d\tau \qquad (1a)$$

where R is the radius of the cylindrical punch, κ is the correction factor for finite thickness effects [6], ν is the Poisson's ratio, G is the shear modulus, T^e is the instantaneous elastic response and δ is the indentation depth. The strain energy functions of various constitutive models were used to define the instantaneous elastic response and compared to identify the optimal fit to the data. The reduced relaxation function was expressed as the following Prony series with a magnitude of one,

$$G(t) = G_\infty + \sum_i G_i e^{-\frac{t}{\tau_i}}. \qquad (1b)$$

The F-statistic was used to determine the optimal number of terms used in the Prony series and compare the QLV versus linear modelling of the stress response with respect to strain [5]. Kolmogorov-Smirnov (KS) statistic with a Bonferroni-corrected p-value was performed to identify any significant differences in the time-dependent shear moduli.

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III. INITIAL FINDINGS

For each indentation plane, the shear moduli were calculated in the brainstem, hippocampus (CA1, CA3, DG), cerebellum (white and grey matter), cortex (white and grey matter), and thalamus (n = 3-7 for each region). The reduced relaxation curves are shown in Figure 1a for each of the aforementioned regions. The shear moduli for each region exhibited a time dependent response. The strain energy density function was used to model the instantaneous elastic response for each of these regions (Figure 1b). The nonlinear stress response increased with increasing depth of indentation. The QLV method provided a better fit to the data than a linear model of stress with respect to strain (data not shown). The Mooney-Rivlin model of the instantaneous elastic response provided a better fit to the data than the Ogden constitutive model (data not shown).

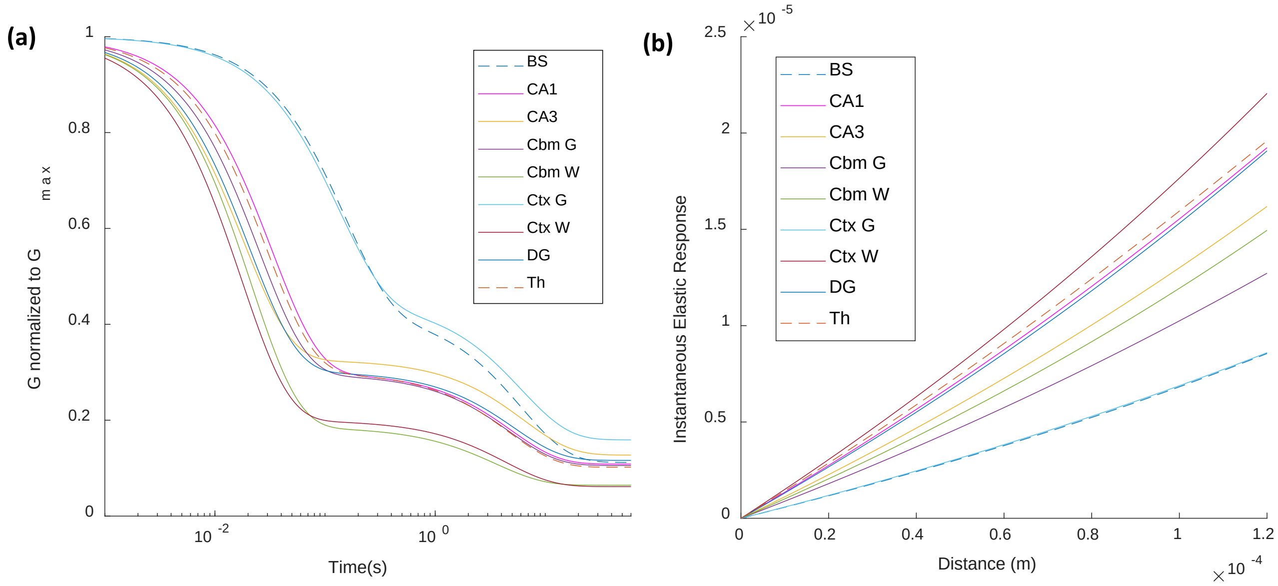

Fig. 1. Reduced relaxation function (a) and instantaneous elastic response defined using the Mooney Rivlin constitutive model (b) for the different regions (BS = brainstem, Ctx = cortex, Cbm = cerebellum, DG = dentate gyrus, Th = thalamus) in the sagittal plane.

IV. DISCUSSION

We determined that the QLV method more accurately modelled the mechanical properties of porcine brain tissue than a linear model with respect to strain elucidating that the brain tissue exhibits a nonlinear instantaneous stress response with strain and a linear viscoelastic response with time. One assumption used in this study is that the area tested underneath the indenter probe was isotropic. This study may be limited by anisotropy present in difference directions within each plane. Further analysis is required to determine if any directional dependencies exist for any anatomical region within porcine brain tissue. To accomplish this, the shear modulus of each region of interest will be compared in the coronal, sagittal and horizontal planes.

V. REFERENCES

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