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Research paper

Mechanical characterization of brain tissue in tension at dynamic strain rates

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ABSTRACT

Mechanical characterization of brain tissue at high loading velocities is crucial for modeling Traumatic Brain Injury (TBI). During severe impact conditions, brain tissue experiences compression, tension and shear. Limited experimental data is available for brain tissue in extension at dynamic strain rates. In this research, a High Rate Tension Device (HRTD) was developed to obtain dynamic properties of brain tissue in extension at strain rates of ≤90/s. *In vitro* tensile tests were performed to obtain properties of brain tissue at strain rates of 30, 60 and 90/s up to 30% strain. The brain tissue showed a stiffer response with increasing strain rates, showing that hyperelastic models are not adequate. Specifically, the tensile engineering stress at 30% strain was 3.1±0.49 kPa, 4.3±0.86 kPa, 6.5±0.76 kPa (mean±SD) at strain rates of 30, 60 and 90/s, respectively. Force relaxation tests in tension were also conducted at different strain magnitudes (10–60% strain) with the average rise time of 24 ms, which were used to derive time dependent parameters. One-term Ogden, Fung and Gent models were used to obtain material parameters from the experimental data. Numerical simulations were performed using a one-term Ogden model to analyze hyperelastic behavior of brain tissue up to 30% strain. The material parameters obtained in this study will help to develop biofidelic human brain finite element models, which can subsequently be used to predict brain injuries under impact conditions and as a reconstruction and simulation tool for forensic investigations.

1. Introduction

Traumatic brain injury (TBI) occurs when a sudden trauma causes damage to the brain. The damage can be focal, confined to one area of the brain, or diffuse, involving more than one area of the brain. Symptoms of a TBI can be mild, moderate, or severe, depending on the extent of the damage to the brain. Most TBIs are due to road transportation accidents but they also occur from workplace or sports accidents and from assaults (O'Riordain et al., 2003; Forero Rueda and Gilchrist, 2009). *Concussion* is the most minor and the most common type of TBI, whereas *diffuse axonal injury* (DAI) is the most severe form of injury which involves damage to individual nerve cells (*neurons*) and loss of connections among neurons. To gain a better understanding of the mechanisms of TBI, several research groups have

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developed numerical models which contain detailed geometric descriptions of anatomical features of the human head, in order to investigate internal dynamic responses to multiple loading conditions (Ho and Kleiven, 2009; Horgan and Gilchrist, 2003; Kleiven, 2007; Kleiven and Hardy, 2002; Raul et al., 2006, 1994; Takhounts et al., 2003; Zhang et al., 2001). However, the biofidelity of these models is highly dependent on the accuracy of the material properties used to model biological tissues; therefore more systematic research on the constitutive behavior of brain tissue under impact is essential.

Over the past three decades, several research groups investigated the mechanical properties of brain tissue in order to establish constitutive relationships over a wide range of loading conditions. Mostly dynamic oscillatory shear tests were conducted (Arbogast et al., 1997; Bilston et al., 2001; Brands et al., 2004; Darvish and Crandall, 2001; Fallenstein et al., 1969; Hrapko et al., 2006; Nicolle et al., 2004; Nicolle et al., 2005; Prange and Margulies, 2002; Shuck and Advani, 1972; Thibault and Margulies, 1998) and unconfined compression tests (Cheng and Bilston, 2007; Estes and McElhaney, 1970; Gilchrist, 2004; Miller and Chinzei, 1997; Pervin and Chen, 2009; Prange and Margulies, 2002; Rashid et al., 2012b; Tamura et al., 2007). However, only a limited number of tensile tests has been conducted (Miller and Chinzei, 2002; Tamura et al., 2008; Velardi et al., 2006). To the authors' knowledge, no experimental data for brain tissue in tension at dynamic strain rates is available except for that of Tamura et al. (2008), who performed tests at 0.9, 4.3 and 25/s, where the fastest rate was closest to impact speeds.

Considering the difficulty of obtaining human brain tissue for *in vitro* testing, experiments are usually performed on animal brain samples (monkey, porcine, bovine, rabbit, calf, rat or mouse). Galford and McElhaney (1970) showed that shear, storage and loss moduli are 1.5, 1.4 and 2 times higher, respectively, for monkeys than for humans. Similarly, Estes and McElhaney (1970) performed tests on human and Rhesus monkey tissue and found that the response of the Rhesus monkey tissue was slightly higher than the response of human brain tissue at comparable compression rates. Differences between human and porcine brain properties were also pointed out by Prange et al. (2000), who demonstrated that human brain tissue stiffness was 1.3 times higher than that of porcine brain. However, Nicolle et al. (2004) observed no significant difference between the mechanical properties of human and porcine brain matter. Pervin and Chen (2011) found no difference between the *in vitro* dynamic mechanical response of brain matter in different animals (porcine, bovine and caprine), different breeds and different genders. Because of the similarities of porcine and human brain tissue, it is convenient to use porcine brain tissue for material characterization and to use these material parameters in human finite element head models.

On a microscopic scale, the brain is made up of billions of cells that interconnect and communicate (Nicolle et al., 2004). One of the most pervasive types of injury following even a minor trauma is damage to the nerve cell's axon through shearing during DAI. DAI in animals and human has been hypothesized to occur at macroscopic shear strains of 10–50% and strain rates of approximately 10–50/s (Margulies et al., 1990; Meaney and Thibault, 1990). Several studies have been conducted to determine the range of strain and strain rates associated with DAI. Bain and Meaney (2000) investigated *in vivo*, tissue-level, mechanical thresholds for axonal injury by developing a correlation between the strains experienced in the guinea pig optic nerve and morphological and functional injury. The threshold strains predicted for injury ranged from 0.13 to 0.34. Similarly, Pfister et al. (2003) developed a uniaxial stretching device to study axonal injury and neural cell death by applying strains within the range of 20–70% and strain rates within the range of 20–90/s to create mild to severe axonal injuries. Bayly et al. (2006) carried out *in vivo* rapid indentation of rat brain to determine strain fields using harmonic phase analysis and tagged MR images. Values of maximum principal strains >0.20 and strain rates >40/s were observed in several animals exposed to 2 mm impacts of 21 ms duration. Studies conducted by Morrison et al. (2000; 2003; 2006) also suggested that the brain cells are significantly damaged at strains >0.10 and strain rates >10/s.

In this study, mechanical properties of porcine brain tissue have been determined by performing tests at 30, 60 and 90/s strain rates up to 30% strain. The loading rates in the present study approximately cover the range of strain rates as revealed during TBI investigations by various research groups (Bain and Meaney, 2000; Bayly et al., 2006; Margulies et al., 1990; Meaney and Thibault, 1990; Morrison et al., 2000; 2003; 2006; Pfister et al., 2003). The challenge with these tests was to attain uniform velocity during the tension phase of the experiments. Therefore a High Rate Tension Device (HRTD) was designed to achieve uniform velocity at dynamic loading velocities during extension of brain tissue. To fully characterize the behavior of brain tissue, material parameters have been determined by fitting isotropic one-term Ogden, Fung and Gent models. Force relaxation tests in tension were also conducted at various strain magnitudes (10–60% strain) with an average rise time of 24 ms. Relaxation data was used to estimate time dependent parameters. Numerical simulations were performed in ABAQUS Explicit/6.9 using material parameters from the one-term Ogden model. This study may provide new insight into the behavior of brain tissue under dynamic impact conditions, which would assist in developing effective brain injury criteria and adopting efficient countermeasures against TBI.

2. Materials and method

2.1. *Specimen preparation*

Ten fresh porcine brains from approximately six month old pigs were collected approximately 6 h after death from a local slaughter house and tested within 4 h, which was consistent with previous work (Estes and McElhaney, 1970; Miller and Chinzei, 1997; Tamura et al., 2007). Each brain was preserved in a physiological saline solution (0.9% NaCl/154 mmol/L) at 4–5 °C during transportation. All samples were prepared and tested at room temperature ~22 °C. The dura and arachnoid were removed and the cerebral hemispheres were first split into right and left halves by cutting through the corpus