

# A QUASILINEAR VISCOELASTIC MODEL FOR BRAIN TISSUE

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## INTRODUCTION

The nonlinear viscoelastic behavior of brain tissue that was observed in oscillatory shear tests was modeled with a quasilinear viscoelastic constitutive relation. The dynamic viscoelastic behavior of brain tissue has been previously modeled with only linear models. The reader is referred to Darvish (2000) for a review of the previous models. Studies on live neural tissue (Thibault *et al.*, 1990) and physical head models with brain surrogate (Margulies, 1987) indicate that brain undergoes finite deformation prior to traumatic injuries. Therefore, it is necessary to use the nonlinear theories to model its mechanical behavior in injurious loading conditions. Recently, the nonlinear viscoelastic behavior of brain tissue at finite strains has been characterized using the results of stress-relaxation tests (Prange *et al.*, 1998). These models, due to the limitations of the test procedure, are not valid for short-time loadings (below 60 ms) that are observed in the events that might lead to traumatic brain injury, e.g., automotive crashes and ballistic injuries. Using the forced vibration method, the brain constitutive model can be improved by broadening its range of validity at the lower end down to about 1-ms (Darvish *et al.*, 1998).

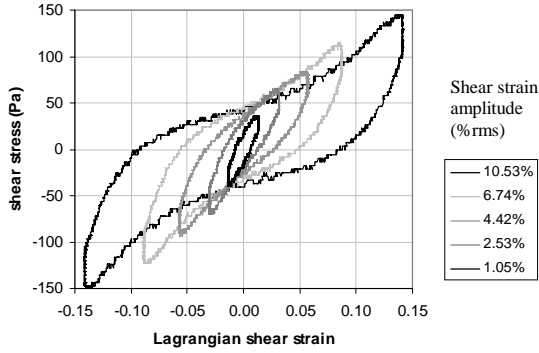
## METHODS

Four disc-shaped samples (15 to 20 mm diameter, 4.75 mm thickness) of cerebral white matter, extracted from two fresh bovine brains (two from each), were tested

in oscillatory shear deformation using a computer controlled electromagnetic vibration system (Darvish, 2000). Samples were kept moist and warm (37°C) throughout the test using a physiological saline solution with chemical composition close to that of the cerebrospinal fluid. Samples were assumed to be homogeneous, isotropic, and incompressible. To account for moderate nonlinearity in shear, a third-order quasilinear viscoelastic constitutive relation was considered. In this model, the instantaneous elastic response was assumed to be a polynomial of the strain, containing the first and the third powers to ensure a symmetric shear response. The linear and the third-order complex moduli were determined in the range of 0.5 to 200 Hz by applying simple, double, and triple harmonic strain inputs with up to 20% maximum peak Lagrangian shear strain. A discrete spectrum approximation was assumed for the relaxation function in the form of Prony Series.

## RESULTS AND DISCUSSION

The Lissajous curves of shear stress versus shear strain (Figure 1) showed significant nonlinear viscoelasticity for brain tissue in shear. The linear complex moduli were modeled with three different exponential decay rates and a constant term in the time domain. Parameter identification of the model was made in the frequency domain by curve fitting the magnitude and phase of the linear complex moduli with trial and error. The proposed average relaxation function can be written in kPa as:



**Figure 1:** Lissajous curves of a brain sample at 5 Hz.

$$\psi(t) = 0.42 + 0.09 \exp(-10t) + 0.01 \exp(-100t) + 31.5 \exp(-5500t) \quad (1)$$

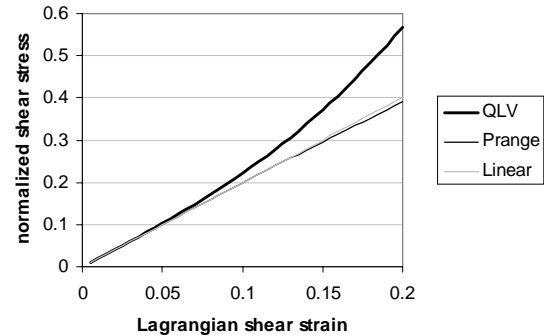
The last term in equation (1) was an indication of a significant transition at about 100 Hz. The average third-order quasilinear complex modulus was determined by trial and error as:

$$E_3(\omega_1, \omega_2, \omega_3) = 10.5 E_1(\omega_1 + \omega_2 + \omega_3) \quad (2)$$

The capability of the proposed quasilinear modulus in predicting the magnitude of the third-order experimental results was significantly better at lower frequencies (below 40 Hz). The variation of the phase of the quasilinear modulus with frequency was always lower than the experimental results. The trend of the observed nonlinearity in the instantaneous elastic response (Figure 2) was significantly different from what was predicted by the model proposed by Prange *et al.* (1998). Our results indicated a stiffening shear modulus from about 5% shear strain while their model predicted a softening shear modulus from about 15% shear strain.

The results of this study showed that a third-order quasilinear viscoelastic model was a good predictor of the magnitude of the nonlinear shear stresses generated in brain tissue for up to 20% shear strain and

frequencies below 40 Hz. This model however was a poor predictor of the phase of the nonlinear response.



**Figure 2:** Normalized instantaneous elastic responses of the proposed model, the Prange *et al.* (1998) model, and the linear model.

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