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Linear Viscoelastic Properties of Cerebral Cortex at Thresholds for Axonal Damage

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Introduction

Traumatic brain injury (TBI) is caused by rapid deformation of the brain that leads to shearing of axons. While deformation below the limits of ultimate failure can activate pathophysiological cascades that cause neurodegeneration [1], bleeding does not always even after tearing of axons. Traditional imaging studies such as CT and MRI are designed to detect areas of bleeding but these can fail to detect the presence of multiple, widespread, microscopic axonal injuries that can result in devastating neurological deficits. A large knowledge gap still exists defining the relationship between axonal injury at a microscopic level (morphological injury) and the material properties of the corpus callosum, hippocampus and cerebral cortex on the macroscopic level, but at identical strain levels. This research investigates the linear viscoelastic properties of the cerebral cortex at known thresholds of axonal injury (0.14 - 0.34 strains [2]). During quasi static loading of tissue in creep tests, instantaneous strains were generated corresponding to axonal thresholds. A linear viscoelastic constitutive model was used to determine six Prony parameters suitable for finite element simulation in ABAQUS and ANSYS. Use of such properties at the levels of axonal damage will help to accurately predict injuries during numerical simulations, to design safety helmets and air bags, and also to refine existing injury criteria and to improve the precision in surgical procedures.

Materials and Methods

Four porcine brains were collected from freshly slaughtered animals. These were preserved in physiological saline solution (0.9% NaCl /154 mmol/L) at 4 to 6°C during transportation. Cylindrical samples of 15 mm diameter and 6 mm thickness were obtained from the cerebral cortex after cutting brain from the sagittal plane in a superior – inferior direction. The opposite side of the sagittal plane, showing the direction of cut and creep testing setup, is shown in Fig. 1. All creep tests were completed within five to ten hours of post-mortem time.

Figure 1. Sample cutting location and Creep testing

Each cylindrical sample was then precisely cut using a scalpel to get consistent thickness. A Hounsfield universal tensile testing machine was used for testing. Upper and lower platens were lubricated using silicon spray lubricant before placement of brain samples for testing. Platens were lubricated to minimize friction and to control the uniform expansion of samples during testing. Each sample was tested at controlled room temperature of 21°C and 55% humidity. A preload force of 0.02 N was applied at each Creep load. Fig. 1 shows a schematic of this protocol.

Linear Viscoelastic Constitutive Model

A six-element, generalized Kelvin model is used for linear viscoelastic analysis of brain tissue. Six Prony constants (material constants) were determined for each experiment using a non-linear least squares fit algorithm in Matlab 7.0. These constants can be used directly for further 3D non-linear viscoelastic analysis of brain tissue for cerebral cortex, hippocampus and corpus callosum by means of stress – relaxation tests at strain levels corresponding to axonal damage.

Figure 2. Generalized Kelvin model and constitutive equation.

\[
\begin{align*}
\varepsilon(t) &= e_0 + e_1 + e_2 + e_3 + e_4 + e_5 \\
\varepsilon_0 &= \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + \varepsilon_5 \\
\varepsilon_1 &= e_1 + e_2 + e_3 + e_4 + e_5 \\
\varepsilon_2 &= e_2 + e_3 + e_4 + e_5 \\
\varepsilon_3 &= e_3 + e_4 + e_5 \\
\varepsilon_4 &= e_4 + e_5 \\
\varepsilon_5 &= e_5 \\
\end{align*}
\]

\[
\varepsilon(t) = e_0 + e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5})
\]

\[
\begin{align*}
\varepsilon_0 &= e_1 + e_2 + e_3 + e_4 + e_5 \\
\varepsilon_1 &= e_1 + e_2 + e_3 + e_4 + e_5 \\
\varepsilon_2 &= e_2 + e_3 + e_4 + e_5 \\
\varepsilon_3 &= e_3 + e_4 + e_5 \\
\varepsilon_4 &= e_4 + e_5 \\
\varepsilon_5 &= e_5 \\
\end{align*}
\]

\[
\begin{align*}
\varepsilon_0 &= e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_1 &= e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_2 &= e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_3 &= e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_4 &= e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_5 &= e_5 \\
\end{align*}
\]

\[
\begin{align*}
\varepsilon_0 &= e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_1 &= e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_2 &= e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_3 &= e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_4 &= e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_5 &= e_5 \\
\end{align*}
\]

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\begin{align*}
\varepsilon_0 &= e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_1 &= e_1(1-e^{-t/\tau_1}) + e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_2 &= e_2(1-e^{-t/\tau_2}) + e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_3 &= e_3(1-e^{-t/\tau_3}) + e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_4 &= e_4(1-e^{-t/\tau_4}) + e_5(1-e^{-t/\tau_5}) \\
\varepsilon_5 &= e_5 \\
\end{align*}
\]

Future Work

The following experimentation and analysis remains to be carried out:-

- Non-linear viscoelastic analysis of brain tissue for cerebral cortex, hippocampus and corpus callosum by means of stress – relaxation tests at strain levels corresponding to axonal damage.
- Hyperelastic testing and dynamic shear testing of these same three regions at strain thresholds corresponding to axonal damage.
- Development of more comprehensive test protocols (size, weight, specimen preparation, air temperature, storage temperature, test duration, humidity, pre-conditioning, post-mortem time, cutting procedure etc.).

Results

Figure 3 compares the creep strains under different load conditions. The creep strain varies from 0.15 to 0.43. Thresholds of axonal damage also fall between these strain limits. Viscoelastic properties within these limits are determined in the form of Prony parameters which are summarized in Table 1. Best least squares fitting is achieved by using a six element generalized Kelvin model in all cases. The fitting of Prony parameters for 0.06 N and 0.07 N load are shown in Fig. 4.

Table 1. Prony parameters at Creep loads.

| Creep load | Prony parameters | Best fit \
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<td>0.03 N</td>
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<td>0.04 N</td>
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<td>0.05 N</td>
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<td>0.06 N</td>
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<td>0.07 N</td>
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<td>0.08 N</td>
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Figure 4. Fitting of Prony parameters to experimental data at axonal damage thresholds.

References


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