BIOMECHANICAL PROPERTIES OF THE HUMAN SPINAL CORD AND PIA MATER

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INTRODUCTION

Spinal Cord Injury (SCI) results from a traumatic insult that causes the neural and/or vascular tissue of the spinal cord to deform beyond their respective physiologic and structural limits. In order to accurately utilize previously reported data on the response of individual neurons, axons and nervous tissue to traumatic forces [1-4] to predict SCI and develop injury thresholds, it is necessary to investigate to what extent forces from the surrounding environment are transmitted to the spinal cord and individual neural elements. This can be accomplished by using biofidelic physical and mathematical models. An integral step in the development of these models is the accurate description of the mechanical properties of the human spinal cord.

To date only two investigators have attempted to quantify the mechanical properties. The first, Breig [5], statically loaded the spinal cord by attaching weights to the thoracic cord. In his experiments, he hypothesized that the pia mater contributed to the tensile strength of the spinal cord. Three decades later, Bilston [6] subjected isolated human spinal cords to stress relaxation tests at strain rates ranging from 0.04 – 0.24 s^{-1} and a maximum strain of 10%.

Due to the limitations of their experimental devices, neither researcher was able to load the spinal cord at a rate comparable to that of a traumatic event (less than 100 msec). To this end, experiments were conducted on human spinal cords to determine the mechanical properties of the spinal cord during traumatic loading and to evaluate the load bearing capacity of the pia mater.

MATERIAL AND METHODS

Human spinal cords were obtained during autopsies from the MCP Hahnemann University Pathology facilities (harvesting and use of cadaveric specimens were approved by the Internal Review Board). Specimens were harvested using an anterior approach from adults ranging in age from 59 – 81 years of age with no history of central nervous system (CNS) injury, CNS disease or infectious disease. The spinal cord with dura mater intact was placed in 0.9% Sodium Chloride and stored at 4 degrees C until testing was performed. Elapsed time from time of death to specimen testing was restricted to less than 48 hours.

Specimens were prepared by excising the dura mater and carefully excising the dentate ligaments and nerve rootlets as close to the spinal cord as possible. Next, the spinal cord was cut into specimens that were approximately 5 cm in length or three spinal segments. This resulted in a length/diameter ratio of approximately five. Specimens were attached at each end to a stiff, wire mesh screen with 4.0 silk sutures. The mesh screens were attached via custom designed grips to a MTS 858 MiniBionix machine fitted with a 25-lb. load cell (Figure 1). Specimens were kept moist with isotonic saline.

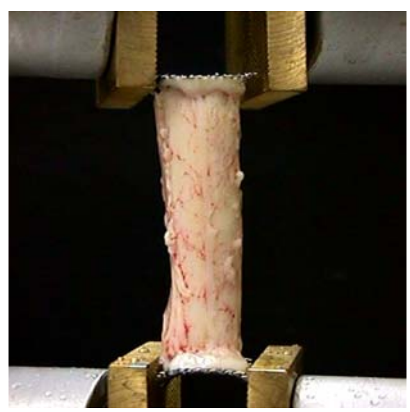

Figure 1. Representative spinal cord specimen

Using displacement control, specimens were axially loaded to a predetermined stretch ratio, λ, at various strain rates. λ is defined as

$$\lambda = L/L_o \quad (1)$$

where L is the measured length of the specimen at any time in millimeters and L_o is the natural length of the specimen hanging under its own weight.

Tests performed on specimens with intact pia mater were loaded to stretch ratios ranging from 1.06 to 1.20 and strain rates of $<0.2s^{-1}$, $1s^{-1}$ and $10s^{-1}$. In order to determine the tensile strength of the spinal cord without pia mater, specimens were loaded in the manner described above and three equidistant, circular incisions were made through the pia mater. These specimens were loaded to a stretch ratio of 1.5 and strain rates of $.1s^{-1}$, $1s^{-1}$ and $10s^{-1}$. All load and displacement data were downloaded at a rate of 1KHz using the MTS Multipurpose Testware software.

RESULTS

A total of 18 specimens were subjected to axial tension (12 with pia mater intact and 6 with incised pia mater). Displacement data were converted to stretch ratio λ according to equation 1. The force data from the load cell were converted to the true stress, σ, defined as:

$$\sigma = F/A \tag{2}$$

where F is the force from the load cell and A is the instantaneous cross-sectional area in meters^2. For an incompressible material, the third strain invariant is equal to 1 and the instantaneous cross-sectional area is related to the initial area by the following equation:

$$A = A_o\lambda_2\lambda_3 = A_o/\lambda_1 \tag{3}$$

λ_1 is the principal stretch ratio in the axial direction and equal to λ described by equation 1 and $\lambda_2\lambda_3$ is the dilatation of the cross-sectional area.

In all of the experiments with the pia mater intact that were subjected to a stretch ratio of 1.10 or higher, plastic deformation was observed as indicated by the final length of the specimen being greater than the initial length. All of the specimens with pia mater incised had structural failure at the end of the test.

ANALYSIS

In order to categorize and compare the data to previous reported data, an estimated elastic stiffness was calculated using a formulation derived by Rivlin [7] in his monograph on elastic deformations of isotropic materials. For a neo-Hookean, incompressible material under simple extension, the stress-stretch ratio relationship has the following form:

$$\sigma = \frac{1}{3}E\left(\lambda^2 - \frac{1}{\lambda}\right) \tag{2}$$

where σ is true stress in Pascals (Pa), E is a constant that represents the elastic stiffness (neo-Hookean elastic modulus also in Pa) and λ is the stretch ratio.

The average neo-Hookean elastic modulus for the specimens with intact pia mater and incised pia mater was 1.40 MPa (SEM 0.088 MPa) and 0.089 MPa (SEM 0.021 MPa), respectively. Figure 2 displays this result (unpaired student T-test $p < .01$). Analysis of the data depicted no statistical significant difference in elastic modulus for specimens loaded at different strain rates.

DISCUSSION

The results of these studies demonstrated no rate sensitivity of the elastic modulus in the axial direction. Although the spinal cord may be rate sensitive at higher rates, loading the tissue at these rates would have little real world correlation. In these experiments, the specimens loaded at a rate of $1s^{-1}$ and $10s^{-1}$ were deformed to a stretch ratio of 1.10 in 100 msec and 10 msec, respectively. In the analysis of controlled car rollover studies, neck loading occurred in 40 – 60 msec.

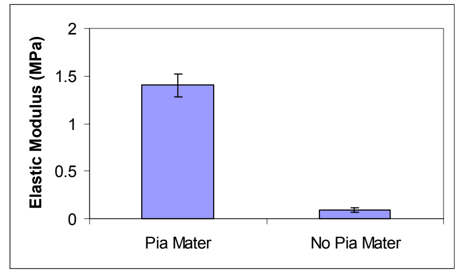

Figure 2. Comparison of Elastic Moduli

As shown in Figure 2, there was a statistical significant difference in the elastic moduli of the specimens with the pia mater intact and the pia mater incised. The average elastic modulus of 1.40 MPa for the specimens with the pia mater intact falls into the range of moduli described by Bilston [6] for specimens loaded at a slower rate (0.52 – 1.88 MPa) and further supports the fact that the spinal cord is strain rate insensitive in the axial direction.

In regards to the specimens with incised pia mater, the average elastic modulus of 0.089 MPa compares favorably to the value of 0.066 MPa described by McElhaney [8] for human brain. Due to the longitudinal alignment of the axons in the white mater and the orientation of the three main blood vessels in the spinal cord, it is reasonable to assume that the neural tissue in the axial direction of the spinal cord would be stiffer than the non-oriented tissue of the brain. It should be noted that these experiments neglect the perfusion pressure of the neural tissue that has been shown to increase the measured stiffness in neural tissue.

These studies indicate that it is the pia mater that gives the human spinal cord tensile strength in the axial direction. The results from this study can be used to construct accurate physical and mathematical models.

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