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Research Paper

Biaxial response of ovine spinal cord dura mater

Snehal S. Shetye[a], **Matthew M. Deault**[a], **Christian M. Puttlitz**[a,b,c,*]

[a]*Department of Mechanical Engineering, Colorado State University, Fort Collins, CO, USA*
[b]*Schoool of Biomedical Engineering, Colorado State University, Fort Collins, CO, USA*
[c]*Department of Clinical Sciences, Colorado State University, Fort Collins, CO, USA*

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ABSTRACT

The dura mater performs a major functional role in the stability and mechanical response of the spinal cord complex. Computational techniques investigating the etiology of spinal cord injury require an accurate mechanical description of the dura mater. Previous studies investigating the mechanical response of the dura mater have reported conflicting results regarding the anisotropic stiffness of the dura in the longitudinal and circumferential direction. The aim of this study was to investigate the biaxial response of the dura mater in order to establish the tissue level mechanical behavior under physiological loading scenarios. To this end, square sections of the dura were tested in a custom biaxial setup under a comprehensive uniaxial and biaxial loading protocol. The resultant data were fit via a transversely isotropic continuum model and an anisotropic continuum constitutive model. The transversely isotropic formulation failed to accurately predict the dura mater's uniaxial behavior. The anisotropic formulation accurately predicted the uniaxial response in both longitudinal and circumferential directions. Significantly higher stiffness ($p<0.0001$) was observed in the circumferential direction as compared to the longitudinal direction. Further, the longitudinal direction displayed a significantly lower degree of nonlinearity ($p<0.045$) and significantly higher degree of collagen fiber dispersion ($p<0.032$) as compared to the circumferential direction. Results indicate that the dura mater has differential mechanical response in the longitudinal and circumferential directions and future studies should utilize an *anisotropic* two fiber family continuum model to accurately describe dura mater mechanics.

1. Introduction

The dura mater plays a major functional role in the spinal cord-meningeal complex (SCM). Being the strongest structure of the meninges, it helps in sustaining the flow and pressure of the cerebral spinal fluid (CSF) and protects the spinal cord from external mechanical loading. Loss of integrity of the dura can result in subdural and epidural hematomas. Accidental damage of the dura during procedures such as lumbar puncture and epidural anesthesia can potentially result in post-dural-puncture headaches (PDPH).

Studies investigating the mechanical response of the spinal cord structure due to traumatic injurious loading to the spine, as well as the aforementioned maladies, require an accurate description of the mechanical behavior of the intact dura. Further, these material models are required for

*Corresponding author at: 1374 Campus Delivery, Colorado State University, Fort Collins, CO 80523-1374, USA. Tel.: +1 970 491 0956.
E-mail address: puttlitz@engr.colostate.edu (C.M. Puttlitz).

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researchers using computational tools (such as the finite element method) and experimentalists that are developing physical surrogate models of the spinal cord (Kroeker et al., 2009). Accordingly, multiple studies have examined the mechanical response of the dura mater. Uniaxial tensile testing of longitudinal and circumferential dura samples from both human and bovine subjects revealed higher stiffness in the longitudinal direction as compared to the circumferential direction (Runza et al., 1999). Similar results were observed by Maikos et al. (2008) with data obtained from rat spinal dura samples. Both studies used histological techniques to observe the collagen orientation and found architectural evidence supporting these anisotropic results. Based on these data, it has been generally accepted that collagen fibers within the dura are preferentially aligned in the longitudinal direction and interspersed with thick elastic fibers. However, more recent studies examining the elastic and viscoelastic behavior of the dura mater in the longitudinal and circumferential directions have reported higher stiffness in the circumferential direction as compared to the longitudinal direction (Persson et al., 2010; Wilcox et al., 2003). Further, histological studies have reported that the dural collagen fibers are not preferentially aligned in the longitudinal direction and that a substantial subset of the total collagen fiber content has been observed to be oriented in the circumferential direction (Fink and Walker, 1989; Reina et al., 1997). Consequently, significant controversy exists as to the true mechanical and ultrastructural relationship of the spinal dura mater.

Physiologically, one might expect that significant loading can occur simultaneously in both the longitudinal and circumferential directions. Radial pressure from the pulsatile flow of the cerebrospinal fluid produces circumferential stresses/strains, and flexural movement of the head/spine can produce tensile loads to the dura in the longitudinal direction. Hence, it is imperative that the dura be mechanically tested in both these directions *simultaneously*, similar to cardiovascular tissues, such that the interaction of these biaxial stresses can be fully appreciated with respect to the overall dural mechanical behavior.

Thus, in order to provide further insight on dura mechanical behavior under physiological loading conditions, the present study investigated the planar mechanical properties of the ovine cervical dura mater by simultaneously (biaxially) testing the dura in the longitudinal and circumferential directions. Further, we quantified the divergent longitudinal and circumferential mechanical response of the dura mater by modifying a previously established two-fiber family strain energy density function that was originally derived to model vascular tissue (Gasser et al., 2006).

2. Methods

2.1. *Specimen preparation*

Four ovine cervical spines were obtained from subjects euthanized for reasons unrelated to this study. Ovine specimens were chosen to ensure continuity with our current efforts in developing computational and experimental models of the ovine SCM. Laminectomies were performed for cervical levels C1–C6 to gain access to the spinal cord complex. Careful dissection of the nerve root connections allowed for the intact removal of the SCM from the associated hard tissue. The dura was detached from the spinal cord after careful resection of the denticulate ligaments. The dural specimens were cut into squares of approximately 25 mm × 25 mm. A small notch, indicating the longitudinal direction, at the periphery of each sample was introduced to ensure that the correct orientation was maintained during the entire preparation and testing period. Specimens were visually evaluated for mechanical integrity and macroscopic abnormalities before being mechanically tested. Three specimens were obtained from each spine, resulting in a total sample size of 12. The thickness of the dura samples (0.35 mm ± 0.09) was measured post hoc to account for saline absorption and tissue swelling during testing (Fig. 1A). Digital images (3 images/specimen, E520 Evolt 10 MP Digital SLR, Olympus, Center Valley, PA) of dural cross-sections were obtained with a microscope (Fisher Scientific, Waltham, MA) and the resultant images processed with ImageJ (NIH, Bethesda, MD) to quantify the mean cross-sectional area, which was used in subsequent stress calculations.

2.2. *Mechanical testing*

A custom biaxial testing device developed by our group was used for mechanically evaluating the dural specimens (McGilvray et al., 2010). The specimens were mounted to the device in a trampoline-like fashion by tying two braided fishing lines (50 lb capacity) per side with a surgeon's knot. The other termini of the lines were attached to the actuating mechanisms (Fig. 1B). The specimen was tested while

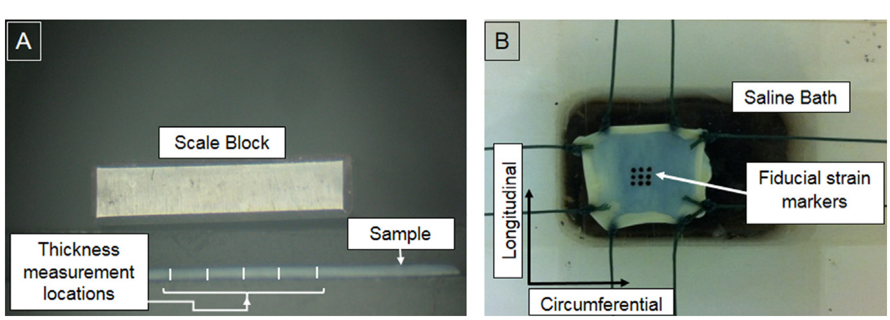

Fig. 1 – (A) Thickness of dura samples measured post hoc at five locations within the vicinity of the stain markers. (B) Dura sample ready to be tested in a custom biaxial test setup.