The Development and Validation of a Physical Surrogate of Human Spinal Dura Mater
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Introduction: The primary objective of spinal surgeries in patients with degenerative spine conditions is to relieve compression on the spinal cord and nerve roots. However, at present, the testing of spinal implants and surgical constructs usually does not include any measure of spinal cord or nerve root compression. Cadaveric spines are used to evaluate the biomechanical performance of different surgical approaches for treating degenerative compression but cadaveric models do not include neurological elements due to the rapid post mortem degradation of the tissue. Surrogate systems have been proposed as a solution to measure cord compression but are either too expensive or not sensitive enough to detect small changes in cord compression. The overall objective of this research is to develop a low cost and accurate surrogate spinal cord system that can detect impingement onto the spinal cord or nerve roots during normal range of motion in-vitro spine tests. Each component of the surrogate spinal cord system is being developed and tested for biomechanical fidelity with fresh tissues. Although studies have demonstrated the significant role of the dura in protecting the spinal cord (1), previous surrogate models of the spinal cord have used a simplified representation of the tissue (2). The objective of this study was to develop and validate a geometrically and mechanically accurate model of the human dura mater for inclusion in the surrogate cord system.

Methods: The results of experimental studies on the mechanical properties of spinal dura mater were used to determine a target material modulus for the surrogate dura at low strains (< 20%) (3, 4). A silicone based material was selected for trial based on its quoted material properties using on a target Young’s modulus of 3MPa. Human cervical dura mater dimensions were obtained from high resolution MRI. Molds were made using a rapid prototyping system (Objet Ltd.) to accommodate the elliptical cross section of the dura. The two part QM 280 silicon was mixed and the cast by painting the liquid silicone into the mold. The mold was closed and set in a custom rotating fixture for 12 hours. This ensured a uniform material thickness as it set. Seven surrogate dura maters were cast to evaluate the variability in performance resulting from the molding process. Three samples were cut and tested from each dura to ensure uniformity along the length of the dura. The surrogate dura mater samples were tested in uniaxial tension to 35% strain (Bose Test Bench). Localized strain was determined using optical tracking. A Young’s modulus was calculated for each dura sample. The variations in modulus between samples from the same dura and across different duras were calculated to determine the reliability of the molding protocol. To determine if the materials would provide an accurate representation of dura mater, the cast dura mater mechanics were compared to experimental data.

Results: The method of molding the dura maters resulted in samples with consistent thickness and mechanical properties. The average dura thickness was 0.35mm ± 0.069mm standard deviation. The dura mater samples showed a nearly linear response to tensile loading at low strains (<20%) but became increasingly nonlinear at higher strains (Figure 1). The variation in material response was less than 10% of the average response at low and moderate strains. The Young’s modulus for the linear range of the tensile response was 2.93MPa ± 0.27 MPa. Variations within samples taken from the same dura were similar to the overall variation observed; demonstrating consistency within each mold and across several mold cycles. The low strain response of the dura mater was similar to the behaviour of human dura tested in the longitudinal direction (Figure 2).
Discussion: The results of this study show that the QM 280 surrogate dura mater provides an accurate representation of the dura mechanical response to tensile loading. Despite injuries to the spinal cord being predominantly compressive, the dura membrane is loaded in tension through deflection of the dura surface. In compression type injuries, the dura surface is moved more than deformed (1) thus the aim was to develop a dura surrogate that accurately captured the low strain behaviour of human tissue. In addition, the dura properties showed very little sensitivity to strain rate (3), thus the material selected here is appropriate for simulating a range scenarios from chronic loading to high rate impacts. The strongly nonlinear response of the dura at high strains was not captured by the QM280 material. This correlation between QM 280 surrogate dura mater and the published low strain tensile characteristics of dura also suggest that the surrogate dura is suitable for models of physiological tensile loading, such as flexion/extension range of motion activities. Previous studies have shown dura mater to be strongly anisotropic with circumferential properties being significantly stiffer than longitudinal properties at high strains; however, the dura does not show the same anisotropy at the low strains considered here (3-6). Therefore the surrogate dura mater proposed here is suitable for simulating human dura mater in a variety of loading conditions from physiological tensile loading to traumatic compression injuries.
Significance: Cadaveric spines are used to evaluate the biomechanical performance of different surgical approaches for treating degenerative compression but cadaveric models do not include neurological elements due to the rapid post mortem degradation of the tissue. An accurate surrogate model of the dura is an critical component of a surrogate model of the human spinal cord complex to use in measuring spinal canal occlusion due to impinging bone and soft tissue structures.

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