Elasticity of the spinal cord dura in the dog

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The elasticity of the spinal cord dura in the dog has been investigated histologically, in situ, and by measurement. The dura was composed of collagenous and elastic connective tissue fibers. The collagenous fibers were arranged in longitudinal bundles, straight when stretched and wavy when unstretched, with a delicate network of fine elastic fibers coursing in all directions. Transecting the cord and dura at T-5 caused a separation of 25 to 30 mm of the dura and a 15- to 20-mm gap in the cord. By means of an appropriate sequence of transections of nerve roots and denticulate ligaments within the dura, and transections of the dural sheaths and nerves outside the dura, the strain on the dura was found to be imposed by the attachments of the dural nerve sheaths from T-6 to S-7. The filum terminale was not appreciably strained. By adding weights to a suspended dura, two components of elasticity were found. For loads of 0 to 50 gm, the incremental displacements in the length were large. The elastic modulus was about $4 \times 10^6$ dynes/sq cm, which was comparable to that of elastic fibers. For loads of 50 to 150 gm the displacements in length were small. The elastic modulus was about $5 \times 10^6$ dynes/sq cm, which was comparable to that of collagenous fibers.

KEY WORDS • dog spinal dura • elasticity • collagen • elastin • cord

TRAUMATIC cord injury, whether due to compression, a blow, or laceration, involves the elastic properties of the dura and spinal cord tissues. Little is known about the elasticity of the dura in man. Various methods have been used in experimental animals to simulate human injuries. These methods have included such procedures as slow compression, dropping weights of known mass from a given height, and simple transection of the cord. The dynamic mechanical properties of dura and cord to such energy changes are reflected in the physical parameters of displacement, velocity, and acceleration. Elastic bodies like the spinal cord and dura will undergo deformation under these conditions, and various kinds of waves may be transmitted for considerable distances. In order to understand the mechanics of the dura and spinal cord relative to injury, the following experiments were performed to define static elastic properties of the spinal cord dura in the dog. The study of the elasticity of the dura was also made for experiments to determine its effect on regeneration and recovery after spinal cord injury.

Materials and Methods

Each dog was anesthetized with pentobarbital sodium, the skin of the back was in-
cised, and the muscles separated from the vertebral spines to the laminae. The spines and laminae were removed to open the extradural space. The exposure usually extended from T-4 to the attachment of the filum terminale. The extradural fat was removed by aspiration to expose the dura.

**Histological Preparation**

For the histological study of the dura, 1 × 1 cm pieces of dura free of nerve roots were cut and pinned to blocks of paraffin in the unstretched condition. Other pieces were fastened to a paraffin block after being stretched in their long axes to their elastic limit. The samples were immersed in 10% formalin for 2 weeks. Frozen sections made with a sliding microtome were washed, stained with orcein and aniline blue, cleared in xylol, and mounted on slides with Permount and a cover slip.

**Demonstration of Elasticity in Situ**

The dura in the dog appeared as a stretched tubular membrane surrounding the cord, with a thin layer of cerebrospinal fluid (CSF) under pressure between the two. A blunt probe was pressed against the surface of the dura until an indentation appeared. The indentation was photographed and the ratio of the longitudinal to transverse axes of the depression was measured. To demonstrate the principal sources of force or stress in the spinal cord dura, the dura, spinal cord, and the attachments were severed in an orderly sequence.

**Elastic Moduli of the Dura**

The dura from T-4 to the filum terminale, about 11 cm long, was removed after severing the spinal nerves and their sheaths close to the dura. One end was fastened to a cross bar of a ringstand and a thread was tied to its lower end. The dura was kept moist with warm Ringer’s solution. Fine needle pointers were attached at right angles to the upper and lower ends of the dura and a metric scale in 0.1 mm steps was placed adjacent to the tips of the two needles. By placing the pointers in the dura, any displacement due to the elasticity of the threads could be disregarded. Weights of different magnitudes were attached to the lower threads, causing the dura to stretch; the incremental displacement for each added weight was measured by noting the values of the needle pointers on the metric scale and subtracting the two values. From these data, the elastic moduli were calculated.

**Results**

**Histological Appearance**

The dura in tangential section was composed of thick bundles of collagenous fibers oriented in the long axis of the dural sheath. Thin elastic fibers were woven in all directions between and around the bundles of collagenous fibers. In the unstretched condition, the collagenous bundles were always wavy (Fig. 1 left). When the dura was stretched in its long axis to its elastic limit (without tearing), the collagenous bundles were straight (Fig. 1 right).

**Elasticity in Situ**

Observations of the elasticity of the spinal cord dura were made in situ. A blunt needle pressed against the dorsal surface of the dura caused an elliptical depression with the long axis in the longitudinal direction of the spinal cord and the short axis in the transverse direction. Photographs of the depression were taken. The lengths of the long and short axes were measured and the ratio determined. The ratio of long:short axes was 7.2:1. The same ratio was obtained after the animal died.

The stress on the spinal cord dura was demonstrated as follows: The dura was slit 1 to 2 cm lengthwise at T-5. The dural slit remained closed because of the longitudinal strain on the dura. When the cord and denticulate ligaments were transected within this slit between the origins of the dorsal and ventral roots, the two ends of the cord separated by 3 to 5 mm (Fig. 2), indicating that the cord itself was under longitudinal strain. When the dura was transected, the rostral and caudal parts of the dura separated 25 to 30 mm and the cord halves by 15 to 20 mm (Fig. 3). In the same preparation, transection of the filum terminale and the enclosed cord caused no separation at this location.

With an intact dura and cord, the filum terminale and its conus could be lifted and stretched 10 to 15 mm with a dural hook without disturbing the position of the rostral dura or cord (Fig. 4). The filum terminale and
Elasticity of spinal dura


The experimental lesions we performed on the cord, dura, nerve roots and sheaths, and denticulate ligaments, with the results on the displacement of the cord and dura are summarized in Table 1. The experiments showed that the dura was stretched longitudinally so that its stretched length was about 30 mm longer than its unstretched length from T-5 to the conus were transected free from the rostral dura and cord resulting in a separation of less than 1 mm for the two ends. The dura was then slit from T-4 to the filum terminale. The dorsal and ventral roots of the spinal cord, but not the denticulate ligaments, were transected within the dura. The rostral part of the spinal cord became separated by a distance of 4 to 5 mm from the conus. Upon transecting the dura, the rostral dura and spinal cord became separated from the filum terminale by a distance of 20 mm.

FIG. 2. Transection of spinal cord at T-6 resulted in 3-mm separation of rostral and caudal parts of the cord.

FIG. 3. Transection of spinal cord and dura at T-6 resulted in 26-mm separation of rostral and caudal dura and 15-mm separation of spinal cord.
**TABLE 1**

*Cord and dura displacement associated with experimental lesions*

<table>
<thead>
<tr>
<th>Lesion</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>spinal cord transected at T-5</td>
<td>5-mm separation of cord</td>
</tr>
<tr>
<td>dura &amp; cord transected at T-5</td>
<td>30-mm separation of dura, 15-mm separation of cord</td>
</tr>
<tr>
<td>dura transected at T-5</td>
<td>20-mm separation of dura</td>
</tr>
<tr>
<td>FT transected</td>
<td>1-mm separation of FT</td>
</tr>
<tr>
<td>FT &amp; conus medullaris transected</td>
<td>1- to 2-mm separation of cord &amp; dura from conus &amp; FT</td>
</tr>
<tr>
<td>conus, FT, &amp; all nerve roots with dural sheaths transected from T-5 to FT</td>
<td>20-mm separation of dura &amp; cord from FT &amp; conus</td>
</tr>
<tr>
<td>nerve roots &amp; denticulate ligaments within dura transected from T-5 to FT; transection of cord at T-5</td>
<td>1-mm separation of cord at T-5</td>
</tr>
<tr>
<td>cord removed from T-5 to FT; transection of dura at T-5</td>
<td>30-mm separation of dura at T-5; removed cord was 3–4 mm shorter than space occupied by cord</td>
</tr>
<tr>
<td>cord removed from T-5 to FT; transection of nerve roots &amp; sheaths outside dura; transection of dura at T-5</td>
<td>30-mm separation of dura at T-5</td>
</tr>
<tr>
<td>cord removed from T-5 to FT; transection of nerve roots &amp; sheaths outside dura; transection of dura at FT</td>
<td>30-mm separation of dura at FT</td>
</tr>
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</table>

*FT = filum terminale.

the rostral end of the filum terminale. The caudal end of the dura was not held in the stretched position by the filum terminale, but rather by the nerve sheaths of the lumbar, sacral, and coccygeal spinal nerves. The filum terminale and the conus were only slightly strained and could be lifted and stretched for a considerable distance without affecting the position of the dura and cord. Transecting the dura at T-5 placed a strain on the non-transected cord by means of the denticulate ligaments. The attachments of the denticulate ligaments between the dura and cord caused the cord to share part of the separation of the dura. Transecting the dura alone transferred the strain of the dura to the cord in the region of the transection through the denticulate ligaments and nerve roots.

**FIG. 4.** Dural hook lifting filum terminale and conus to demonstrate the lack of strain in the dura of this region.

**FIG. 5.** Graph showing incremental elongation of isolated 12-cm piece of thoracolumbar dura for different loads. Elongation from 0 to 50 gm was due to elastic fibers, from 50 to 150 gm to collagenous fibers. Δl: increment of elongation; l₀: initial length.
Elastic Moduli of the Spinal Cord Dura

Figure 5 shows the incremental changes in length of an 11-cm piece of thoracolumbar dura upon loading it with different weights from 1 to 150 gm. From 1 to 50 gm the length increased rapidly, and from 50 to 150 gm only a very slight increase in length occurred. The first part of the curve with loads of 1 to 50 gm was attributed to the elastic fibers, and the second part with loads of 50 to 150 gm was due to the collagen fibers. The cross-sectional area of the dura at T-6, measured with a micrometer and a metric scale, was 3.78 sq mm. The elastic modulus, calculated for loads from 20 to 30 gm in the first part of the curve, was $3.99 \times 10^8$ dynes/sq cm. The modulus for the second part for loads from 50 to 150 gm was $4.63 \times 10^8$ dynes/sq cm.

Discussion

Elasticity plays a major role in the vascular system, where the elastic, collagenous, and smooth-muscle fibers contribute in different ways to normal function. The arrangement, amount, and elastic moduli of each component furnish certain properties to the walls of the arteries that determine the character of the pulse wave, the blood-pressure fluctuations, and the volume, velocity, and acceleration of blood flow. The vascular system is predominantly a dynamic system where energy fluctuations are rapid and repetitive.

The dura and spinal cord are part of a dynamic mechanical system, although this character is not as apparent. The dura and spinal cord are generally only seen in the myelogram, during neurosurgery, and at autopsy. Therefore, only their static properties are evident. The normal energy fluctuations are relatively slow as in walking and turning, but may be fairly rapid as in the case of active exercise, such as running, jumping, and diving. The dynamic properties have not been studied, but probably show marked changes during violent accidents to the body, neck, and vertebrae. In experimental animals, dropping weights, compression, and severing the cord release the strain imposed on the cord and dura, and also cause waves to be transmitted in the medium for considerable distances.

The present experiments have demonstrated that the cord dura in the dog is under longitudinal strain, due to the attachments of the dural sheaths of the spinal nerves. The elastic fibers appear to be stretched almost to the limit of their elasticity. This means that in a normal state, the elasticity of the cord dura is determined by the collagenous fibers, except for the moderately strained filum terminale in which the elastic fibers still retain considerable elasticity. Measurements of the elastic moduli of the cord dura have confirmed the existence of two phases of elasticity. For loads of 0 to 50 gm, the elastic modulus, $3.99 \times 10^8$ dynes/sq cm, was comparable to that found by Harkness, et al., for the elastic fibers in arteries, $3 \times 10^8$ dynes/sq cm. For loads of 50 to 150 gm, the elastic modulus, $4.63 \times 10^8$ dynes/sq cm, was comparable to the modulus for collagenous fibers ($10^9$ dynes/sq cm).

Consequences of the collagenous control of the dynamic elastic properties of the dura and cord in the normal condition would be expected in its response to blows, in rupture of the collagenous fibers, and in loss of the elastic fiber component. These conditions and their effect on cord function are being investigated.

The spinal cord is under strain within the dural sheath and also may have a degree of elasticity of its own. By transecting the cord and denticulate ligaments within the dura, the rostral and caudal segments of the cord separated by 4 to 5 mm. Part of the separation was due to strain transmitted to the cord by the denticulate ligaments and the dural root sheaths. The spinal cord from T-4 to the conus, detached from its denticulate ligaments and spinal roots, is shorter by only a few millimeters.

It may be concluded that if the dura is seriously avulsed or torn in the dog, the longitudinal strain of the dura would be transferred to the spinal cord in the region of the avulsion. If the cord has also suffered severe lacerations, hemorrhages, or necrosis reducing its viscosity, the strain of the dura may be of sufficient magnitude to cause the spinal cord to yield and rupture.

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References


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