Mechanical and physiological effects of dentatotomy

JOSEPH F. CUSICK, M.D., JAMES J. ACKMANN, PH.D., AND SANFORD J. LARSON, M.D., PH.D.

Department of Neurosurgery, Medical College of Wisconsin, Milwaukee, and Veterans Administration Hospital, Wood, Wisconsin

The role of the dentate ligaments in the pathogenesis of myelopathy secondary to disease conditions that alter the normal biomechanics of the spinal canal was studied in 14 dogs. The effects of posterior cord elevation on somatosensory evoked potentials (SSEP's) and tension requirements were compared before and after dentate ligament section in acute experiments. At levels of posterior elevation usually within the confines of the canine canal, the dentate ligaments were the most significant element increasing tension requirements and SSEP alterations. Human cadaver studies also showed an approximate 50% reduction of force after dentatotomy. These findings suggest that after dentate ligament section the applied tension is distributed over a longer segment of the cord with a reduction in tension and disruption of axonal conduction at the level at which the force was applied.

KEY WORDS • dentate ligaments • myelopathy • cervical spondylosis • evoked potentials

Several contributing factors have been proposed to explain the development of myelopathy in disease states that alter the normal biomechanical relationship of the spinal cord and the spinal canal. The myelopathy associated with cervical spondylosis has been attributed to stenosis of the canal, tethering by the dentate ligaments, nerve root adhesions, hypertrophy of the ligamentum flavum, and spinal cord ischemia secondary to compression of the anterior or lateral spinal arteries. Controversy exists as to whether patients with spondylotic myelopathy should be operated on. Opinions differ among those who favor surgical treatment as to the approach, and, in the case of laminectomy, as to whether the dentate ligaments should be divided. If the patient is to be treated surgically, the operation should be designed to correct the abnormality primarily responsible for the myelopathy. Gas myelography has been helpful in demonstrating the various mechanical and structural alterations and their relationship to spinal cord distortion. In many gas myelograms the spinal cord has been shown to be closely adherent to the floor of the canal regardless of body position, implying a tethering effect by the dentate ligaments. Some clinical observations suggest tethering of the spinal cord by the dentate ligaments, as illustrated by the following case report.

Case Report

A 46-year-old man was evaluated in June, 1973, because of pain in the neck and upper
limbs and weakness of the arms. The intrinsic hand muscles were atrophic and sensory perception was decreased in the lower cervical segments. A gas myelogram demonstrated a narrow spinal canal with multiple anterior protrusions from C-4 through C-7. A laminectomy was performed from C-4 through C-7, but despite this procedure the symptoms and findings became worse. He was admitted to our hospital in June, 1974. His gait was spastic and ataxic. The forearm and hand muscles were weak and atrophic; this was most pronounced in the intrinsic hand muscles. The deep reflexes were hyperactive and clonus was sustained in both ankles. Perception of pain was diminished from C-5 through C-7. Perception of vibration and joint rotation was diminished in both lower limbs. Gas myelography was repeated (Fig. 1 left). At a second operation, the laminectomy was extended to include C-3, and the dentate ligaments were divided bilaterally from C-3 through C-7. The width of the previous laminectomy appeared adequate and was not enlarged. A postoperative gas myelogram demonstrated that the spinal cord had moved away from the spondylotic ridges (Fig. 1 right). The patient improved.
Effects of dentate section

progressively; he became able to walk independently and had improved perception of joint rotation. Clonus disappeared on the left and was intermittent and unsustained on the right.

Because of these observations, experiments were conducted in dogs and human cadavers to evaluate the influence of the dentate ligaments on spinal cord biomechanics and function.

Methods and Materials

Barbiturate anesthesia was induced in 14 mongrel dogs. Each animal was intubated and maintained on a respirator. A Silastic catheter was introduced into the femoral artery for continuous blood pressure monitoring and periodic blood gas determinations. With the spine in a moderate degree of flexion, a six-level cervicothoracic laminectomy was performed in each animal. After the dura was opened, an electrode array consisting of two platinum-iridium discs, 1 mm in diameter and 0.025 mm thick, 5 mm apart on center and embedded in Dacron-reinforced Silastic, was placed over the dorsal surface of the spinal cord at the superior limit of the laminectomy. These electrodes were used for recording evoked potentials secondary to stimulation of the peroneal nerve. Rectangular constant current pulses of 100 msec duration, 4 Hz, were applied transcutaneously to the peroneal nerve. The stimulus intensity was greater than that required to obtain a motor response in the hind limb (5 to 10 mA peak). Averaging computer techniques were used to record the responses.11

Group 1

In eight dogs, two nylon slings separated by two pairs of dentate ligaments were passed under the spinal cord in the mid-portion of the laminectomy. The slings were connected to a Grass model FT 10 force transducer* with micrometer drive which was suspended from a frame secured to the spinous processes at the upper and lower limits of the incision. Measurements of tension were taken at each 0.8-mm increment of elevation of the cord from the floor of the spinal canal. The transducer output was recorded on a strip chart. Corresponding peroneal nerve-to-cord evoked-potential responses were recorded at each increment of elevation. When the amplitude of evoked responses was reduced to approximately 40% of control, the cord was returned to its original position and additional responses were recorded until a maximum recovery of amplitude was obtained, usually slightly less than that of the initial control value. The dentate ligaments between the slings were then divided and the procedure repeated.

Group 2

In three animals, a single nylon sling was placed about the cord in the upper thoracic region. Tension measurements and corresponding evoked-potential responses were obtained at 0.8-mm intervals of elevation until response amplitude was reduced to approximately 40% of control. Evoked potentials were recorded at 10, 20, and 30 minutes while elevation was maintained. The dentate ligaments were then divided above and below the sling and recordings of tension and evoked potentials were repeated until the values became stable.

Cadaver Studies

Cervical laminectomy from C-2 to T-1 was carried out in three fresh human cadavers. Two nylon film slings separated by two pairs of dentate ligaments were placed about the cord. Tension recordings were made with the same frame and force transducer, as before with the neck flexed and extended before and after division of the intervening dentate ligaments.

Results

Animal Studies

Group 1. Before dentate section, mild to moderate posterior elevation of the cord resulted in reduction of the evoked-potential amplitude. This reduction began before the posterior surface of the cord had reached the measured posterior limits of the canine vertebral canal. After dentate section, similar changes in the evoked-potential response did not occur until greater degrees of posterior elevation and recorded tension had been reached.

*Grass model FT 10 force transducer manufactured by the Grass Instrument Corp., Quincy, Massachusetts.
Fig. 2. Group 1 dogs. Graph compares the reduction of the evoked-potential response after posterior cord elevation with two slings before and after dentate ligament section. Data are given as the mean ± 2 SE from eight dogs.

Fig. 3. Group 1 dogs. Graph shows the increase in the force required for posterior cord elevation before dentate ligament section. Data are given as the mean ± 2 SE from eight dogs.
Effects of dentate section

A comparison between posterior elevation measured at 0.8-mm increments and the percentage decrease in the amplitude of the evoked-potential response before and after dentate ligament section is shown in Fig. 2. As indicated the differences before and after section are statistically significant. After dentate ligament section, the evoked response was not affected until the cord had been elevated 3.2 mm; after this level was exceeded, the two curves had a similar shape. This relationship suggests that the mechanisms responsible for the evoked-potential changes are the same before and after dentate section, the difference being the amount of posterior elevation and applied force required.

In three early experiments (not included in the results) elevation to the point of the maximum depression of the amplitude of the evoked response was carried out before dentate ligament section. When the amplitude suppression exceeded 70% to 80%, significant recovery toward control did not occur after reduction of the elevation, suggesting axonal disruption.

Length/tension recordings in all animals consistently showed a greater force requirement at specific levels of cord elevation before dentate ligament section (Fig. 3). Although the differences were not as pronounced as the corresponding changes in evoked potentials, the dentate ligaments did appear to restrict posterior migration of the cord.

**Group 2.** The recovery of evoked-potential amplitude after dentate ligament section while the cord remained elevated is shown in Figs. 4 and 5. The residual amplitude reduction is approximately the same as that observed following elevation after dentatotomy in the Group 1 animals. Compared to the findings in Group 1 where two slings were placed around the cord, larger forces and greater elevation of the cord from the floor of the canal were required in Group 2 before significant evoked-potential changes occurred. This is consistent with the experimental observations of others that the degree of spinal cord deficit is proportional to the number of cord segments involved. The residual tension after dentate ligament section in this group reflects the effect of other restrictive forces on posterior displacement of the cord (Fig. 6), and is comparable to the length/tension values before and after dentate section.

![Fig. 4. Group 2 dogs. Recordings of the evoked-potential responses with associated posterior cord elevation by a single sling. Dentate ligaments sectioned at 8.0-mm elevation with subsequent responses show rapid and progressive recovery. Analysis time is 62 msec.](image-url)
Fig. 5. Group 2 dogs. Graph shows the effect of dentate ligament section after 8.0-mm cord elevation. Data are given as the mean ± 2 SE from three dogs. Section of one pair of adjacent ligaments resulted in significant response recovery (A) which was even greater after section of the second pair of ligaments (B).

Fig. 6. Group 2 dogs. Graph shows the effect of ligament section at 8.0-mm of cord elevation with a single sling. Data are given as the mean ± 2 SE from three dogs. Section of one pair of adjacent ligaments resulted in significantly reduced tension requirements (A) which was even greater after section of the second pair (B). Brackets = standard error of the mean.
Effects of dentate section

**Fig. 7.** Data from three human cadavers. Graph shows the characteristic increase in force requirements for posterior cord elevation before dentate ligament section with the neck in moderate flexion.

**Cadaver Studies**

In cadavers, for a given increment of posterior displacement, the tension was greater before the dentate ligaments were cut. With moderate degrees of cord elevation, the tension decreased markedly after dentate section (Fig. 7). The tension in the elevated cord was increased when the spine was flexed and was reduced with extension both before and after dentate ligament section.

**Discussion**

In 1947, Kahn proposed that the dentate ligaments firmly fixed the cord against any anterior compressing lesion, and therefore prevented equal transmission of applied pressures. He charted lines of stress, showing that the maximum burden was incurred by the posterolateral region with relative sparing of the anterior columns. Bedford, et al., later supported this concept and suggested that because of this fixation, the cord was vulnerable to normal neck movements.

Reid found in cadaver dissections that the length of the spinal canal greatly increased in flexion, mainly between C-2 and T-1. The anterior component of the force exerted by the cord and dura undergoing a 3-mm displacement with the neck in flexion was found to reach a maximum of 30 to 40 lbs/sq in. With the neck in the neutral position, an anterior pressure of 2 lbs/sq in. was exerted by the cord and dura. These force measurements referred only to the pressures between the anterior dura and the wall of the spinal canal. The contribution of other factors, such as the dentate ligaments that might be acting between the cord and canal, were not investigated. He did feel, however, that the normal function of the dentate ligaments appeared to be the transmission of axial stresses between the cord and canal rather than that of providing a mechanism to hold the cord in any particular dorsoventral position.

In studies of the normal biomechanics of the spinal cord, Breig demonstrated that the cord does not move in the longitudinal axis, but adapts itself to the length of the spinal canal by plastic deformation. In extension, the cord is compressed axially and transverse folds appear on its surface, and in flexion the cord is drawn out smooth again. He felt that compression of cord tissue in many instances sets up local axial stresses. His cadaver studies revealed that in flexion of the spine, the lateral bands and dentate attachment are straightened both axially and transversely with a slight resultant tension set up in them. This tension as well as the position of the dural attachment of the dentate ligament, which is slightly nearer the ventral than dorsal regions, results in a retaining action by these ligaments. Thus the cord with the spine in flexion does not yield beyond the middle of the canal. Stoltmann and Blackwood were unable to demonstrate in cadaver studies any limitation of movement of the spinal cord by the dentate ligaments in the anteroposterior direction. They used en bloc sections of the cervical and upper thoracic vertebral columns with the spinal cord in situ. Both posterior and anterior bone removal and subsequent intradural exposure were carried out in
formalin-fixed preparations and the anterior exposure in frozen specimens. The restrictive action of the dentate ligaments was then examined without subjecting the canal to alterations of functional position. In the opinion of those investigators, the probable function of the dentate ligaments is to limit the movement of the spinal cord in the longitudinal axis. Following this study, increasing attention was paid to other potential etiological factors, and many authors considered dentatomy either incidental to laminectomy or even contraindicated because some manipulation of the cord might be unavoidable.

Our findings are consistent with Breig's observations. Relatively acute dorsal elevation of the cord with intact dentate ligaments produced an early decrease in evoked-potential amplitude that was not observed after dentate ligament section. These alterations in evoked response suggest interference with axonal conduction from segmental axial stress which is reduced by division of the dentate ligaments. In the animal experiments, the dentate ligaments appear to be an important restrictive element operating at low levels of applied force and posterior elevation. When this restrictive influence is removed, greater degrees of posterior elevation and applied force are necessary before similar changes occur.

As previously noted, Breig has shown that in flexion with elongation of the canal the distance between the dentate attachments to the dura increases and an axial pull is exerted which gives rise to transverse tension in the lateral bands of ligaments. The ligaments have then been placed in a position of tension giving strength and rigidity to these structures. These ligaments consist of collagen arranged in parallel bundles. Collagen supplies strength and rigidity in tension and in tension alone. Normally, all adjacent structures share in the distribution of the tensile forces unless certain individual ligaments are placed under a greater degree of tension, causing a local increase in rigidity. Such a localized increase in tension could be associated with elevation of the cord by a ventral elevating force, particularly while the cord is in ventroflexion. The tension is therefore greatest in the locally elevated portion of the cord, and decreases with distance from it.

Fibrous tissue also follows what has been called the stretch hypertrophy rule. Living fibrous tissue structures when exposed to a series of intermittent elevating tension loads undergo additional formation of collagen. This increases the tension strength and tensile rigidity of the cross-sectional area. As rigidity increases, the amount of elongation developed under subsequent loads of similar magnitude will decrease. Although such alterations occur only with intermittent tension loads, it appears reasonable to assume that the dentate ligaments in certain instances of cervical spondylosis undergo stretch hypertrophy, resulting from tension occurring intermittently when the cord is in ventroflexion. Such a mechanism could offer a possible explanation of the clinical pathological findings of Bedford, et al. These authors noted that the most significant areas of cord degeneration were those regions adjacent to thickened dentate ligaments. Their findings conform with other clinical pathological studies demonstrating that the areas of maximum pathological changes are in the lateral, posterolateral, and medial posterior columns with sparing of the anterior columns.

The present experimental observations showing the restrictive influence on posterior cord elevation by the intact dentate ligaments were made while the cord was exposed to stretch forces of a relatively acute and intermittent character. The influence of the ligaments on segmental axial stress may not be as great in a chronically distorted cord. In that instance, a slowly increasing displacement of these fibrous tissue structures might not result in the intermittent tension loads necessary for stretch hypertrophy and might therefore undergo tensile stress leading to attenuation.

Although corresponding spinal cord blood flow studies were not performed, it does not appear likely that such rapid recovery after 10- to 20-minute periods of interrupted function would be due to a reversal of cord ischemia. In addition, because of the rich radicular blood supply, ischemia of the canine cord should be difficult to produce with the relatively small forces used in this study. The major influence appears to be mechanical stress applied to the posterior and lateral columns of the spinal cord. The rapid recovery of the evoked-potential response after dentate ligament section was associated
Effects of dentate section with reduced spinal cord tension. These observations may have significance with regard to the type of surgical therapy to be used. Because of the well established intolerance of the spinal cord to anoxia, reversal of the myelopathy would not be expected to follow improved blood supply after prolonged ischemia. However, a reduction of segmental pathological axonal tension would offer potential reversal of the myelopathy if the axons were still anatomically intact.

Selection of the appropriate surgical procedure for the treatment of spondylotic myelopathy depends upon accurate definition of the major biomechanical abnormality. If a laminectomy is done, then division of the dentate ligaments appears justifiable, particularly if gas myelography demonstrates persistent adherence of the spinal cord to the floor of the spinal canal.

Acknowledgment

The authors wish to thank Kathrin Gvadia for her excellent technical assistance.

References

12. Mair WGP, Druckman R: The pathology of spinal cord lesions and their relation to the clinical features in protrusion of cervical intervertebral discs. (A report of 4 cases.) Brain 76:70–91, 1953
17. Reid JD: Effects of flexion-extension movements of the head and spine upon the spinal cord and nerve roots. J Neurol Neurosurg Psychiatry 23:214–221, 1960

Address reprint requests to: Joseph F. Cusick, M.D., Department of Neurosurgery, The Medical College of Wisconsin, 8700 West Wisconsin Avenue, Milwaukee, Wisconsin 53226.