Extensibility of the lumbar and sacral cord

Pathophysiology of the tethered spinal cord in cats

SATOSHI TANI, M.D., SHOKEI YAMADA, M.D., PH.D., AND ROBERT S. KNIGHTON, M.D.
Section of Neurosurgery, Loma Linda University School of Medicine, Loma Linda, California

Tethered spinal cord, or tethered cord syndrome, describes a disorder manifested by progressive motor and sensory deficit in the legs and by incontinence. Tethered cord syndrome occurs when the elongated spinal cord is anchored by a thick filum terminale or other pathological structures. The underlying mechanism is impairment of oxidative metabolism in the lumbosacral cord. The authors studied the extensibility of various parts of lumbar, sacral, and coccygeal segments in experimental animals and correlated this with the oxidative metabolism in these segments.

The ilium terminale possesses far greater extensibility than any spinal cord segments and functions as a buffer in preventing the cord from overstretching. The lumbar, sacral, and coccygeal segments elongate under traction only below the attachment of the lowest pair of dentate ligaments. The lower the cord segment, the greater the percentage of elongation in spite of limited elasticity of the cord tissue; this greater percentage of elongation of the spinal cord correlates with increasing impairment of the oxidative metabolism and more severe neurological deficit. These findings explain such symptoms and signs as motor and sensory deficits in the legs associated with the human tethered cord syndrome, and correspond with the high clinical incidence of incontinence.

The lower spinal cord segments elongated promptly within 3 seconds after the start of traction. This implies that repeated acute hyperextension and hyperflexion, as occurs in humans, may accentuate oxidative metabolic changes that have already been caused by chronic cord tethering. The authors conclude that the elongation of the spinal cord under traction parallels the degree of metabolic dysfunction.

KEY WORDS - spinal cord extensibility - tethered spinal cord - oxidative metabolism - lumbosacral cord lesion - cat

The symptomatology includes: dysfunction limited to the lumbosacral cord; a high incidence of incontinence; or motor and sensory dysfunction, which is frequently unrelated to the myotomal or dermatomal pattern or to the manifestation at the cord level. Thus, our laboratory has concentrated upon the following questions to elucidate the pathophysiology of tethered cord syndrome: 1) What part of the spinal cord is affected by tethering? 2) Are metabolic effects related to the extent of spinal cord elongation? 3) Does acute stretching of the spinal cord contribute to neuronal dysfunction in a manner similar to that produced by chronic tethering?

In this presentation, extensibility and recovery of segments of the lower thoracic, lumbar, sacral, and coccygeal cord produced by acute experimental tethering are measured. Data are considered in terms of metabolic and neurological effects of tethering.
Pathophysiology of tethered spinal cord

Materials and Methods

Thirty-three adult cats, each weighing between 2.5 and 3.5 kg, were initially anesthetized with ketamine hydrochloride (Vetalar, 30 to 40 mg/kg), intubated intratracheally, and then artificially ventilated with nitrous oxide and oxygen (3:1) through a pediatric ventilator. Gallamine triethiodide (Flaxedil, 0.5 to 1.0 mg/kg) was injected intermittently through a cannula into a femoral vein to immobilize the animal. Two pairs of prongs were inserted against the T-13 vertebra and the sacrum. These prongs were fastened to a Horsley-Clarke type of apparatus for immobilization of the lumbar and sacral spine.

After a T13–S3 laminectomy was performed, the dura was incised and opened in the midline and the filum terminale was ligated with 5-0 silk thread. This ligation was positioned 5 mm caudal to the attachment of the lowest (the sixth or seventh) coccygeal nerve (Cy6 or Cy7), which was considered to be the lowest end of the cord. The experimental model of spinal cord tethering was devised in the manner described previously. Traction was applied to the spinal cord of the cats, simulating the tethered cord syndrome in humans. One end of a 2-0 silk ligature was tied around the ilium terminale at a location 5 mm below the attachment of the lowest coccygeal nerve root in the majority of the cats. The other end was passed over a pulley and attached to a weight varying from 1 to 15 gm. The pulley was clamped to a stand, and its height was adjusted so that the direction of the traction and the long axis of the lumbosacral cord formed a straight line.

The following nomenclature was used, depending on the location of the ligature, to determine the divisions: 1) Division 1 (0), Division 2 (0), etc., with the ligature placed immediately below the attachment of the lowest coccygeal nerve root; 2) Division 1 (5 mm), Division 2 (5 mm), etc., with the ligature 5 mm below; 3) Division 1 (10 mm), Division 2 (10 mm), etc., with the ligature 10 mm below. However, the second category was considered to be the standard and the parenthesis was not inserted, unless compared with the elongation of the divisions with other ligature locations.

The lengths of the cord segments were measured, including T-13 through the third coccygeal nerve (Cy3), and the total length of Cy4, Cy5, and Cy6. Each cord segment was identified by the attachment of the corresponding nerve root. The T-13 root was located at its dural exit into the T-13 foramen, and the others were placed according to their corresponding foramina. Cord segment dimensions from Cy3 to L-5 were measured according to the distance between the attachments of the most cephalic and most caudal rootlets. The method of Thomas and Combs was used to measure cord segments above L-5, since there is a space between the attachment of the highest and the lowest rootlets of the rostral nerve root. The L-5 cord segment was measured as the distance between the highest rootlet of the L-5 and the highest rootlet of the L-6 nerve root. Measurements were made with a micro-ruler (with an accuracy of 0.5 mm) under surgical microscopic observation. The spinal cord segments caudal to the S-1 segment (S-2 to Cy3 segments) were identified in only four cats. In the other cats, manipulation of the arachnoid membrane and nerve roots around these segments was avoided to prevent any possible changes in extensibility of the spinal cord.

Two methods were used to determine the extensibility of the spinal cord. One was to measure the sequential rapidity of elongation of each cord segment during traction of either 3 or 5 gm. To accomplish this, a Sony television (TV) screen was connected to a JVC video camera, which was attached to the ceiling frame 1 m above the operative field and immobilized. Twelve 10-0 nylon sutures were placed as markers at 10-mm intervals through the pia mater in the midline. These nylon sutures were tied on the free 3-mm-long 2-0 silk thread so that they were clearly visible on the TV screen. The markers were numbered from 1 to 12, with the first being 10 mm cephalad to the tethering point (Marker T). The division between Marker T and Marker 1 was designated as Division 1 and that between Markers 1 and 2 as Division 2, etc. (Fig. 1). Continuous
recording of the exposed cord segments was made during 15-minute periods of 3- and 5-gm traction in three cats each. The video tape was later replayed, and the length of each division was measured at 1-second intervals after the start of traction.

The other method to determine extensibility required the measurement of each cord division during traction with weights ranging from 1 to 15 gm. Since nearly maximum elongation of the divisions was noted within 2 minutes of traction (Fig. 3), these measurements were made at the end of a 2-minute period of traction with the following weights: 1, 2, 3, 5, 10, and 15 gm. Reversibility of cord elongation was evaluated in the following manner. At the end of 5 minutes of traction, the weight was removed. Measurements were repeated for 5 minutes following release of 3-gm traction in two cats and of 5-gm traction in three cats.

To isolate the extensibility of the filum terminale, the ligature was placed 10 mm below the attachment of the lowest coccygeal nerve in three animals and 5-gm traction was applied. In three other cats, the ligature was placed immediately below the attachment of the lowest coccygeal nerve and 5-gm traction was applied. This allowed study of the extensibility of the spinal cord itself, simulating human tethered cord syndrome. As in previous experiments, 10-0 silk sutures were placed at 10-mm intervals from the site of the ligature in order to produce traction. The elongation of each division was measured 2 minutes after the start of traction.

The protective mechanism of the dentate ligaments against traction was evaluated in the following manner. Ligatures were placed 5 mm below the attachment of the lowest coccygeal nerve in one animal and immediately below that in another animal, and then 5-gm traction was applied after section of the three or four lowest dentate ligaments; the lower T-13 and upper L-1 cord segments were still held by intact dentate ligaments. Elongation of each division was measured at 2 minutes after the start of traction.

S. Tani, S. Yamada and R. S. Knighton
Pathophysiology of tethered spinal cord

**Results**

**Relationship Between Spinal Cord Segments and Markers**

The distance between the tethering point (5 mm below the attachment of the lowest coccygeal nerve) and the middle of the L-I cord segment was 123 ± 2.1 mm (mean ± standard error of the mean in 20 cats). The cephalic end of the filum terminale was usually located at the S-1 vertebra and only rarely at L-7.

The relationship between cord segments and their lengths is shown in Fig. 2. The mean length of the L-1 cord segment was 16.1 ± 0.4 mm, that of the Cy3 segment was 4.3 ± 0.1 mm, and that of the Cy4, Cy5, and Cy6 segments was 13.0 ± 0.2 mm, corresponding to the results of Thomas and Combs. The length of each spinal cord segment was greater than that of the adjacent caudal segment. In Fig. 2, the term "coccygeal cord (Cy)" is used for the segment caudal to the sacral cord, instead of the phrase "caudal cord" which has been used in anatomy books.

The dentate ligaments were identified in 13 cats. The lowest dentate ligament was attached to the dura mater at the L-6 spinal cord segment in all cases. In eight of 13 cats, a ligament 1 mm thick that was similar to, but slightly firmer than, the arachnoid membrane spanned the L-7 segment and the inner surface of the dura about 7 mm caudal to the cord attachment.

**Sequential Changes During Traction**

In general, the lower division elongated more rapidly than the higher division. Elongation extended farther into the higher divisions during 5-gm than during 3-gm traction.

**Traction at 3 Gm.** Elongation profiles of each division during 3-gm traction are shown in Fig. 3 left. Elongation of Divisions 1, 2, and 3 reached 3.0%, 2.5%, and 1.3% of their original lengths, respectively, within 1 second after weight application. Elongation of Divisions 1 and 2 continued to 5.6% in 2 seconds and to 8.1% in 3 seconds, after which the cord length remained stable. About 80% of the total elongation in Divisions 1 and 2 occurred within 3 seconds. The elongation of Division 3 reached a plateau at 2 seconds but increased again at 20 seconds and reached another plateau at 2 minutes. The elongation of Divisions 4 and 5 reached plateaus at 5 and 10 seconds, respectively.

**Traction at 5 Gm.** The elongation profiles during 5-gm traction are shown in Fig. 3 right. The elongation of Division 1 was much greater and more rapid than that of Division 2, reaching 13.5% in 2 seconds and a plateau at 5 seconds; after 30 seconds it gradually increased to 21.3% at 5 minutes. About 74% of the total elongation in Division 1 occurred within 3 seconds. Elongation of Division 2 was 7.9% at 2 seconds but it only gradually increased until 1 minute after weight application. The percentage elongation of Division 3 under 5-gm traction was greater than that of the same Division under 3-gm traction; the percentage elongation of Divisions 4 and 5 under 5-gm traction was similar to that under 3-gm traction.

**Elongation of Cord Segments Relative to Traction Weights**

The filum terminale was torn immediately rostral to the tethering point within 2 minutes of applying continuous 10-gm traction in five of 10 cats, and within 2 minutes of applying 15-gm traction in the remaining cats. Elongation of Division 1 increased linearly with increase of traction weight from 1 to 10 gm. The higher the division level, the less likely there was a linear relationship between the percentage elongation and the traction weight. A plateau was noted between 5- and 10-gm traction in the other divisions (Fig. 4). There were, however, a few exceptional cases; for example, Division 3 elongated more than Division 2, and the percentage elongation of Divisions 4, 5, and 6 were reversed in Cat 9.

It is worth noting that the variable elongation of different cord segments may indicate that neuronal dysfunction does not always occur in contiguous cord
segments. This may explain irregular motor and sensory deficits in clinical cases being neither myotomal nor dermatomal, nor in a cord level distribution.\textsuperscript{23}

Reversibility of Cord Elongation

The percentage elongation during traction and the percentage contraction after release of traction are shown in Fig. 5 left for 3-gm traction and in Fig. 5 right for 5-gm traction. These measurements were made 5 minutes after the start of traction and 5 minutes after the release of traction. All divisions regained their original length after release of 3-gm traction. Only the higher divisions (Divisions 4 through 7) regained their original length after release of 5-gm traction. The lower divisions remained elongated (about 7\% of the original length in Division 1, and 3\% in Divisions 2 and 3).

Elongation of the Filum Terminale

A linear relationship was noted between the elongation rate of Division 1 (10 mm) and the traction weights from 1 to 3 gm (Fig. 6). When traction weights of more than 3 gm were applied, the slope of the percentage elongation increased more than those of Division 1 (5 mm) and Division 1 (0). Two of three animals were subjected to traction with more than 5 gm, and the filum terminale was torn at 7- and 10-gm traction.

Elongation of Cord Segments

During traction with the ligature at the lowest end of the spinal cord, a linear relationship was noted between the elongation rate of Division 1 (0) and traction with weights from 1 to 5 gm (Fig. 7). When the weight was further increased, the slope of the percentage elongation decreased. To evaluate elongation of the lumbar, sacral, and coccygeal cord with the dentate ligaments released, four pairs of dentate ligaments were sectioned up to the level of Division 12, and the elongation extended further cephalad to Division 11 (5 mm) and Division 12 (0) (Fig. 8). This was contrary to the elongation seen as high as Division 7 (5 mm) in those spinal cords with totally intact dentate ligaments. It is of interest to note that the elongation rate of the lower cord segments such as Divisions 1 and 2 in the former group was not as great as in the latter.

![Figure 5](image-url)

**Fig. 5.** Percentage elongation (at 5 minutes after the start of traction) and recovery rate (at 5 minutes after release of traction) of each division during 3-gm traction in three animals (left) and during 5-gm traction in three animals (right).

![Figure 6](image-url)

**Fig. 6.** Percentage elongation of each division (10 mm) during traction with 1 gm through 5 gm in three animals.
Pathophysiology of tethered spinal cord

Discussion

The results presented here demonstrate several processes. 1) The lower the segment, the greater was the percentage elongation under traction. 2) The greater the traction weight, the greater was the elongation of each lumbosacrococcygeal segment and, consequently, the greater the percentage elongation of these entire cord segments below the attachment of the lowest dentate ligament. 3) The percentage elongation of the spinal cord divisions did not form a linear relationship with the traction weight increase. The elongation was greater up to 3-gm traction and became less between 3- and 5-gm traction and then even less between 5- and 10-gm traction. The only exception was Division 1 (0), where the elongation rate was linearly increased as the traction weight increased. 4) The filum terminale elongated linearly as the traction weight increased, similar to a rubber band. 5) The extent of elongation increased rapidly within 10 seconds and less thereafter until 5 minutes when elongation reached maximum. 6) The lower the segment, the more rapid was the elongation. The higher the divisions, the more delay there was in elongation. The greater the traction weight, the higher was the extent of elongation of cord segments. 7) Direct traction to the spinal cord caused the lowest segment to elongate in a manner similar to the filum terminale within a limited range of traction weights. 8) After release of 3-gm traction all cord segments resumed their original lengths, but after release of 5-gm traction the lower cord segments remained slightly elongated.

It is apparent that two structures, the filum terminale and the dentate ligaments, function as buffers to prevent excessive elongation of the spinal cord while the spine alternately hyperextends and hyperflexes. The filum terminale, because of its rubber-band-like extensibility, alleviates excessive elongation of the spinal cord. The
dentate ligaments, which suspend the cervical, thoracic, and upper lumbar segments as caudal as Division 6 (the L-6 cord segment), counteract the caudal traction force. This function of the dentate ligaments is further illustrated by findings that, when four pairs of dentate ligaments are sectioned, the spinal cord elongation extends further cephalad, up to Division 12 (the L-1 cord segment), where the lowest of the remaining dentate ligaments are attached.

Viscoelasticity of the spinal cord also acts to prevent excessive elongation, since the viscosity of the spinal cord is greater than that of a rubber band: the higher the cord segment the more delay in elongation. Another protective mechanism of the spinal cord may be the large bulk of spinal cord tissue in the lumbosacral enlargement which resists overstretching.

If the spinal cord is subjected to structural abnormality, such as produced by traction without the filum terminale as a buffer, the lowest cord segment, Division 1 (0), elongates similar to the filum terminale as a compensatory mechanism. Acute tethering, which produces the majority of total elongation within 3 seconds, can be very traumatic to the cord tissue, especially when stretching occurs repeatedly in the chronically tethered cord. This experimental situation appears to correspond to the human tethered cord syndrome, where the tip of the spinal cord is anchored by the thick filum terminale.

A remaining question is whether the greater elongation rate of the spinal cord segments corresponds to more severe neurological dysfunction. Yamada, et al., 20,23,24 found that more pronounced derangement in the interneuron potentials and redox state of cytochrome $aa_3$ occurred in the sacral cord segments during traction than in the lumbar segments. Sensory stimulation caused profound deterioration in oxidative responses in cytochrome $aa_3$ and in interneuron potentials when recorded in the sacral cord segments, 25 but such effects were not consistently observed in the lumbar segments (M Rosenthal, et al., personal communication, 1985). On the other hand, hypoxic stress during 3- and 5-gm traction produced alteration in redox activity of cytochrome $aa_3$ in all segments. 20,23,24 After release of 5-gm traction, the lower cord segments did not resume their original lengths. This could be expected when reviewing the failure of recovery in oxidative metabolism after release of 5-gm traction. 12,20

We postulate that the greater the elongation of the spinal cord segment, the greater the tensile force in the cord tissue. In humans as well as in experimental models, the lumbosacral cord suffers from excessive tensile force by traction. 1,4,8,17,16 and spinal cord function is impaired both metabolically and physiologically. 20,23,24 These metabolic and physiological changes and the elongation rates of lower cord segments may correlate with a high incidence of incontinence in humans as a manifestation of S-2, S-3, and S-4 cord dysfunction. 9,16,23,25

Metabolic and physiological changes are similar to those that occur under ischemia or hypoxia. 14,21,22 Also, chronic experimental cord tethering results in persistent metabolic dysfunction similar to that in acute cord tethering. 12 It is conceivable that in the human tethered cord, as in the chronic model of cord tethering, repeated hyperextension and hyperflexion produce additional tensile force and precipitate metabolic dysfunction leading to neuronal damage.

References

17. Smith CG: Changes in length and position of the segments of the spinal cord with changes in posture in the monkey. Radiology 66:259-266, 1956
Pathophysiology of tethered spinal cord

25. Yashon D, Beatty RA: Tethering of the conus medullaris within the sacrum. J Neurol Neurosurg Psychiatry 29: 244-250, 1966

Manuscript received January 31, 1986.
Accepted in final form September 2, 1986.
Address for Dr. Tani: Jikei University School of Medicine, Nishi-Shinbashi, Minatoku, Tokyo, Japan.
Address reprint requests to: Shokei Yamada, M.D., Ph.D., Section of Neurosurgery, Loma Linda University Medical Center, Loma Linda, California 92350.