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Pathophysiology of "tethered cord syndrome"

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The tethered cord syndrome is a clinical entity manifested by progressive motor and sensory changes in the legs, incontinence, back or leg pain, and scoliosis. In order to elucidate the pathophysiology involved in the tethered cord, the reduction/oxidation ratio (redox) was used *in vivo* of cytochrome a,a_3 to signal oxidative metabolic functioning in human examples of tethered cord and in animal models. Studies in experimental models indicate marked metabolic and electrophysiological susceptibility to hypoxic stress to lumbosacral cord under traction with greater weights (3, 4, or 5 gm). Similar effects were demonstrated in redox behavior of human tethered cord during surgical procedures. The authors conclude that symptoms and signs of tethered cord are concomitant with lumbosacral neuronal dysfunction which could be due to impairment of mitochondrial oxidative metabolism under constant or intermittent cord stretching. It is assumed that prolonged or accentuated neuronal dysfunction may lead to structural damage to the neuronal perikarya and later of the axons. Untethering procedures in human tethered cord improve oxidative metabolism, and probably facilitate the repair mechanism of injured neurons.

KEY WORDS • **tethered cord syndrome** • **spinal cord metabolism** • **spinal cord potential** • **redox of cytochrome a,a_3** • **spinal cord injury**

INCREASING evidence supports the concept that progressive motor and sensory changes in the legs and incontinence may be caused by tethering of the spinal cord, especially in young children.[1,15,19,21,22,24,33,42,49] In 31 cases, Hoffman, *et al.*,[19] observed the conus medullaris fastened by the thick filum terminale to the sacrum. Based on remarkable neurological improvement after release of cord tension by sectioning the filum, they concluded that the neurological deficit was effected by cord tethering. They used the term "tethered spinal cord" for tethering-induced symptomatology.

Tethering is also produced by firm fibrous bands or by a bone spicule attached to the spinal cord, or scarred nerve roots.[1,15,22,41] All of these may often be associated with spinal dysraphism,[1,22,41] a spinal cord tumor,[1,4,7,14,21,25,34,40,41,47] myelomeningocele,[21,24,33] and an elongated cord.[15,19,22,32,42] We have managed 13 cases with similar neurological findings and operative results, in which cord tethering was produced by these various factors, in addition to the thick filum. In this report, we include these cases in the category of "tethered cord syndrome."

The question remains as to the cause of tethering-induced dysfunction of the spinal cord. Impairment of blood flow,[12,27,39] function,[12,26,27,31,43] and metabolism[20,50] has been observed in the traumatized or compressed cord. Many studies have demonstrated that impaired circulation in the brain leads to progressive functional and morphological deterioration and finally to cell death.[6,9,11,13,16,18,28,30,36–38,51] In spite of this background work, it has not been determined whether oxidative metabolism is changed with tethering and whether cell injury results from such changes. Any change could be of great significance, because we have demonstrated a tight coupling between electrophysiological function and metabolism in the spinal cord with normal circulation,[35,45] and because it is generally believed that neurons (and glia) rely entirely on energy derived from intramitochondrial adenosine diphosphate (ADP) phosphorylation. Therefore, if tethering results in metabolic deficiency, then progressive neuronal injury is likely to follow.

To approach this question, we have used changes in the reduction/oxidation (redox) ratio of cytochrome a,a_3, the terminal oxidase of the respiratory chain, as a signal of metabolic functioning in experimental and clinical examples of tethered cord. We report here that

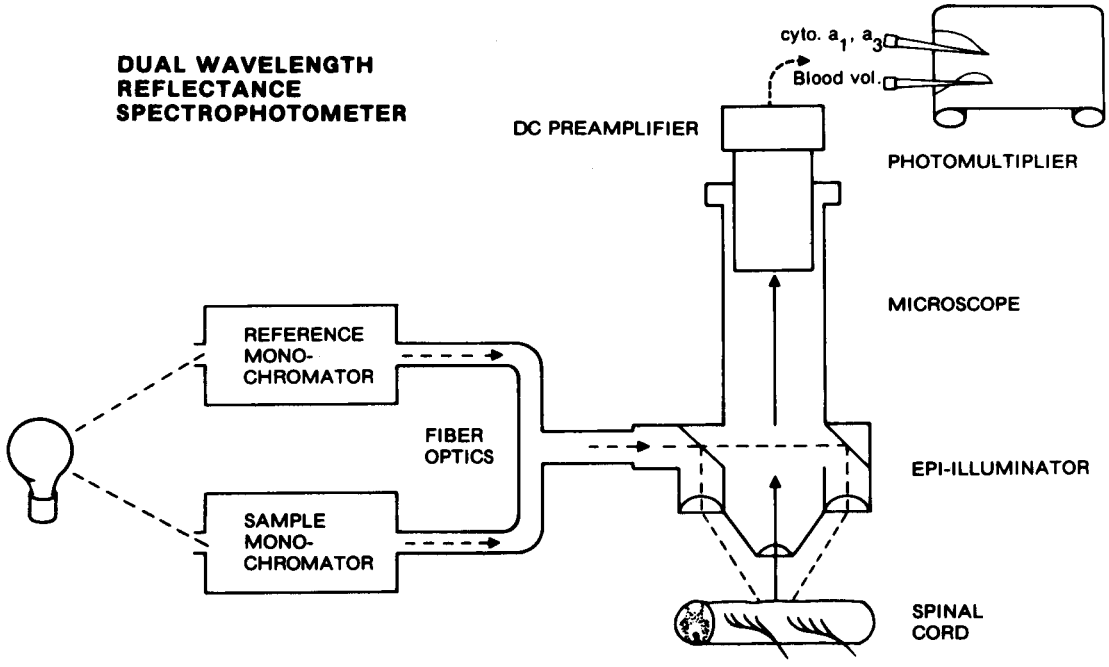

FIG. 1. Diagram showing the set-up for the dual wavelength reflection spectrophotometer.

oxidative activity is altered by cord tethering, and changes consistent with "improved" metabolic functioning are produced by untethering.

Materials and Methods

Dual wavelength reflection spectrophotometry was used for these studies. This noninvasive optical technique provided a continuous signal of intracellular metabolism, by monitoring the reduction/oxidation (redox) ratio changes of cytochrome a,a_3. Light beams from two monochromators, at 605 nm and 590 nm, respectively, were provided alternately to an area 3 mm in diameter at the upper sacral segments or at the junction of the lumbar and sacral cord segments in cats and in humans (Fig. 1). Reflected light at each wavelength was collected by a microscope objective and monitored for intensity by a photomultiplier tube. Changes in the redox ratio of cytochrome a,a_3, recorded as the difference between the intensity of light reflected at 605 nm and 590 nm, provided a "reference" wavelength "equibestic" to changes in blood volume and hemoglobin oxygenation.[23] Changes in the difference signal were expressed as percentages of full scale, with zero being the condition when full reference but no sample light was presented to the cord, and 100% being the condition when equal reference and sample illumination were recorded by the photomultiplier tube while the tissue was in a "resting" state before experimental manipulation.

Human Tethered Cord

Clinical Data. Cytochrome a,a_3 studies in seven patients with tethered cord are presented here (Table 1). The patients' ages ranged from 2 to 26 years. Of these patients, four were male and three female. Their symptoms and signs included weakness or leg-muscle atrophy or both (five cases); sensory deficit (two cases); back or leg pain (two cases); urinary incontinence (four cases); diminished rectal tone (three cases); scoliosis (seven cases); leg deformity (four cases); hypo- or areflexia (six cases); and Babinski sign (two cases). Causes of tethering were: 1) thickened filum terminale (one case); 2) the filum terminale replaced by fibrous bands (three cases); 3) lipomatous filum associated with a sacral lipoma (one case); and 4) thick fibrotic filum associated with lipomyelomeningocele (two cases). Other associated anomalies were: spina bifida (seven cases), and elongated spinal cord (seven cases). Arachnoid adhesion was noted in all patients but one who had a lipomatous filum; severe arachnoid adhesion was noted in three patients in whom the filum was replaced by the fibrous band.

Redox of Cytochrome a,a_3. Each of the surgical patients or their families agreed that the patient undergo these redox studies. The sacral cord was exposed through laminectomy for untethering procedures under anesthesia with 70% N_2O and 30% O_2. Spectrophotometric measurements were made at the upper sacral cord. The spectrophotometry time was limited to approximately 15 minutes.

TABLE 1

*Clinical observations in seven patients with tethered cord**

Case No.	Sex, Age (yrs)	Leg Weak or Atrophied	Sensory Change (pain)	Urinary Incontinence	Anal Tone	Leg Deformity	Scoliosis	Deep Tendon Reflex	Thick Filum	Arachnoid Adhesions	Cord Level	Mass Lesion
1	M, 2	+	−	+	−	−	+	↓(B)	+	++	S-3	
2	F, 2	−	−	+	−	−	+	normal	+	++	S-1	lipomyel
3	M, 7	+	−	−	−	−	+	↓	+	++	S-2	
4	F, 11	±†	−	−	++	+	+	↓	+	+	L-5	
5	F, 12	+	+	+	++	+	+	↓(−A)	+	−	S-1	lipoma
6	M, 14	++	−(+)	−	+	+	+	↑(↓A)	+	++	L-3	
7	F, 27	+	+(+)	+	−	+	+	↓(−A) (B)	+	++	L-5	lipomyel

*++ = marked; + = present; − = not present; ↓ = decreased; ↑ = increased; A = Achilles jerk; B = Babinski sign; lipomyel = lipomyelomeningocele.

†Retrospective evaluation, see text.

Hypoxia on Tethered Cord and Untethered Cord. Mild hypoxia was produced for 3 minutes by changing the fraction of oxygen in the respired gas mixture (FiO_2) from 30% to 15%. After hypoxia, FiO_2 was increased to 60% for 2 minutes and then was returned to 30%. This sequence of changes was repeated after untethering procedures. In Case 1, the first hypoxia study was repeated at 30 minutes under identical conditions. In Cases 2 and 6, tethering was reproduced by suturing the proximal end of the sectioned filum to the distal end after the hypoxic study of the untethered cord, so that another hypoxia study could be performed on the retethered cord. This was done because we wished to determine whether or not the redox study carried out before untethering (no reduction as illustrated in Fig. 3) was valid.

Experimental Tethered Cord

Experimental Preparation. Twenty-five cats were each anesthetized with Ketalar (ketamine hydrochloride) and their tracheas intubated. They were then respired with a 3:1 ratio of N_2O and O_2 through a Harvard pump respirator.* Cannulae were placed in the femoral artery and vein. Arterial pO_2 was sampled at intervals and was maintained at approximately 100 mm Hg by manipulation of the respiratory volume and rate. The cat was paralyzed initially with an intravenous injection of Flaxedil (gallamine triethiodide, 20 mg), followed by administrations of 10 mg to obviate cat movements during recordings. Two pairs of prongs were inserted through small skin incisions against the L-1 vertebra and the sacrum, and fastened to a Horsley-Clarke-type apparatus for immobilization of the lumbar spine. The lumbosacral cord and the filum terminale were exposed through laminectomy. If dorsal roots were crowded over the dorsal surface of the cord, the arachnoid membrane was initially cut longitudinally in the midline under the surgical microscope. The crowded dorsal roots were gently pushed away from the cord surface with a pointed glass dissector for maximum exposure of the area to be examined by spectrophotometry.

Tethering of the Spinal Cord. 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 filum terminale, and the other end was passed over a pulley and attached to a weight varying from 1 to 5 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 (Fig. 2).

After the redox baseline of cytochrome a,a_3 was established, one of the weights was applied for traction. Thirty seconds after onset of traction, the animal was respired with 100% N_2O for 2½ minutes. This was followed by respiration of 100% O_2 for 1 minute, and then by the initial 3:1 ratio of N_2O and O_2. This protocol was found to be the best compromise between amplifying the extent of metabolic changes and eliminating the fall in blood pressure below 60 mm Hg for prevention of cord damage, which generally occurred when 100% N_2O was given for longer periods. Two minutes after the normal ratio of N_2O:O_2 (3:1) was resumed, traction was released. After a 30-minute period without traction, the hypoxia study was repeated with traction.

When the above recordings were finished, hypoxia was produced until the redox ratio of cytochrome a,a_3 reached its highest plateau (at PaO_2 = 15 mm Hg or less, with blood pressure below 60 mm Hg) and then traction was applied. This was done to rule out artifactual changes in cytochrome a,a_3 redox ratio during the traction, because the field of observation without

*Harvard pump respirator manufactured by Harvard Apparatus, Inc., 150 Dover Road, Millis, Massachusetts.

TABLE 2

Surgery and results in seven patients with tethered cord

Case No.	Sex, Age (yrs)	Operative Procedures	Postoperative Results
1	M, 2	removal of fibrous band that had replaced the filum	increase in muscle bulk in both legs within 2 mos; incontinence cleared
2	F, 2	removal of fibrous band that had replaced the filum & of lipomyelomeningocele	gained bladder control within 2 wks
3	M, 7	section of several fibrous bands, one of which was the scarred filum, at S-2 level; dissection of severe arachnoid adhesion at L3–S2 levels	increase in thigh & leg muscles within 3 mos, especially in dorsiflexors of the left foot, toes, & calf muscles, which had been markedly atrophied
4	F, 11	section of thick filum; removal of fibrous structures around it	within 3 mos, increased muscle bulk in legs, particularly both gastrocnemii and dorsiflexors of both ankle joints
5	F, 12	section of thick filum; removal of lumbosacral lipoma	muscle bulk in legs increased & sensory changes subsided within 3 mos
6	M, 14	section of thick filum	muscle bulk of thighs & legs increased within 2 mos; leg pain subsided within 3 wks; 2 years later twisting of left ankle while walking (hyperabduction) no longer noticeable
7	F, 27	section of thick filum; removal of lipomyelomeningocele	within 3 months, motor power & sensation in the lower extremities improved except for anesthesia in S3–5 areas; pain disappeared; pes equinus became less marked; urinary control improved

traction moved about one-fourth of its diameter on application of 5-gm traction.

Cord Potentials. Cord potential recordings were taken from the dorsal cord in response to stimulation of the L-6 or L-7 dorsal root. An Ag-AgCl electrode was placed on the dorsolateral surface of the cord, and an indifferent electrode was positioned in close proximity to the recording electrode. The dorsal root was stimulated with a single rectangular pulse (1 msec).[29,45]

Results: Human Tethered Cord

Clinical Observations

A summary of the surgery performed and the results of the untethering procedures are given in Table 2.

Untethering Procedures. Extensive dissection of severe arachnoid adhesions under the surgical microscope was required in three cases to free the conus

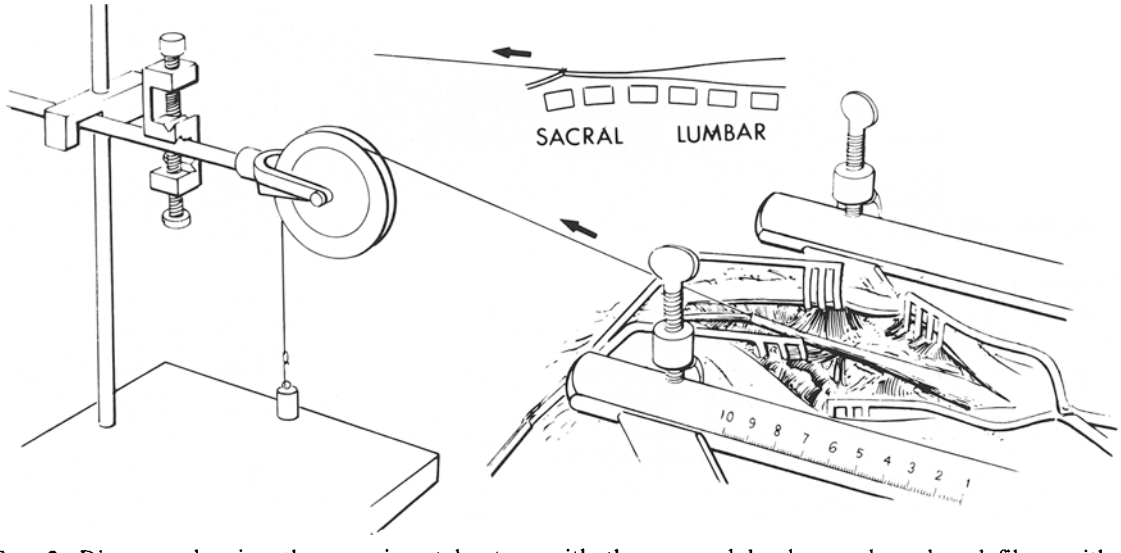

FIG. 2. Diagram showing the experimental set-up with the exposed lumbosacral cord and filum with traction applied.

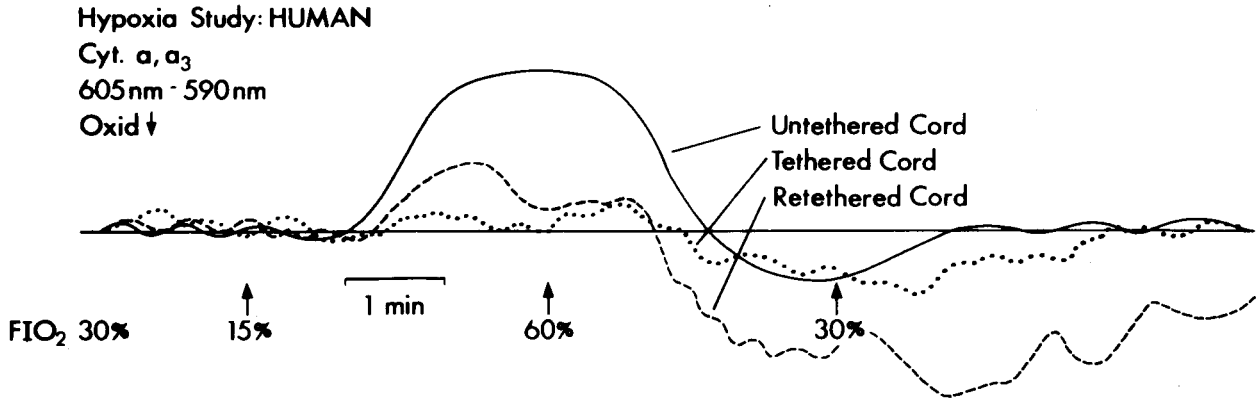

FIG. 3. Redox changes during hypoxia in one group of the human tethered cords (Type 1). No redox change is seen before untethering *(dotted line)*, but reduction similar to that in normal cat cords (see Fig. 5) is noted after untethering *(solid line)*. No reduction occurs while the cord is temporarily retethered *(interrupted line)*. FIO_2 = fraction of oxygen in the respired gas mixture.

medullaris, nerve roots, and filum terminale. However, sectioning of the filum terminale or the filum replaced by fibrous bands was essential for cord untethering. In order to prevent retethering from postoperative adhesions, the arachnoid membrane and the dura were closed separately using 8-0 nylon and 5-0 silk, respectively. If an arachnoidal or dural defect occurred after untethering procedures, a Silastic sheet was substituted for the pia arachnoid and a fascial graft for the dura mater to fill in the defect.

Operative Results. Significant increase in strength and muscle bulk in the lower extremities was noted within 3 months in six cases. One case (Case 4) seemed to have adequate leg strength preoperatively, but developed increased muscle bulk within 3 months postoperatively. Sensory deficit subsided within 3 months (Cases 5 and 7), and pain was alleviated within 4 weeks (Cases 6 and 7). Urinary control became normal or nearly normal within 1 month in four of five cases. One patient (Case 7) experienced improvement in urinary control but is performing self-catheterization every 3 to 4 hours without incontinence in the intervals.

Deformity of the lower extremities included pes equinus (Cases 5 and 7), hyperabduction of the ankle (Case 6), and inadequate dorsiflexion of the ankle joints (Case 4).

These leg deformities became less noticeable in all four cases postoperatively. Inadequate dorsiflexion of both ankle joints in Case 4 was so subtle that the patient and her parents admitted this deformity only 1 month after operation when dorsiflexion was noted to have increased more than 10° to surpass the neutral position (90°). Scoliosis in all seven cases became less marked after operation, but the younger the patient at the time of operation, the more marked the improvement.

Redox of Cytochrome a,a_3 with Hypoxic Stress

Figures 3 and 4 show typical examples of redox changes of cytochrome a,a_3 previous to, during, and following mild hypoxia in patients undergoing untethering procedures. Before untethering, there was no change (Type 1, Fig. 3) or only a mild change (Type 2, Fig. 4) in the redox state of cytochrome a,a_3 toward reduction when FiO_2 was decreased from 30% to 15%. The Type 1 redox change was noted in Cases 2 and 6, and Type 2 in Cases 1, 3, 4, 5, and 7. After untethering, however, the cytochrome a,a_3 became rapidly reduced during hypoxia (PaO_2 = 60 mm Hg at the end of hypoxia) and returned to the baseline after reoxygenation. These changes toward normal redox responses during the FiO_2 changes were noted in all seven cases studied in this series. In Case 4, reduction of cytochrome a,a_3 was delayed during hypoxia before untethering but reached almost the same plateau as that obtained after untethering. As previously mentioned, this patient presented with minimum symptoms. Two patients suffered retethering, and a hypoxic study was repeated for redox of cytochrome a,a_3, but little redox response was noted, as shown in Fig. 3. In Case 1, redox changes in two hypoxia studies before untethering were found to be identical. During and after the hypoxic studies, none of the patients showed changes in blood pressure and pulse rate.

Results: Experimental Tethered Cord

Redox Ratio of Cytochrome a,a_3

Cord without Traction. Figure 5 shows the redox changes of cytochrome a,a_3 in the spinal cord without traction under hypoxic stress. After 100% N_2O inhalation started, the level of reduced cytochrome a,a_3 began to rise and reached a plateau when PaO_2 fell to

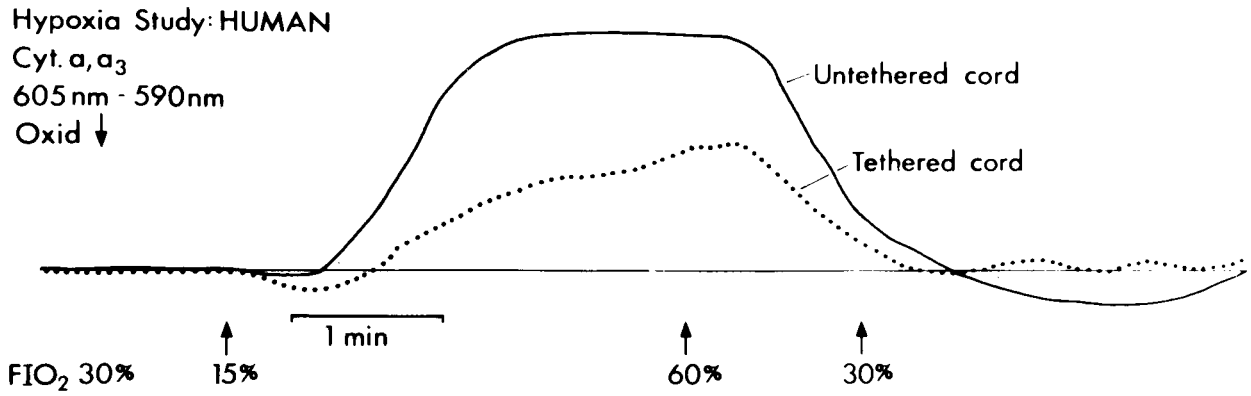

FIG. 4. Redox changes during hypoxia in the other group of human tethered cords (Type 2). Only a mild redox change is noted before untethering, but reduction is noted after untethering, as in Type 1. FIO_2 = fraction of oxygen in the respired gas mixture.

25 mm Hg or below. A plateau was reached at approximately 2½ minutes, during anoxia. Following reestablishment of O_2 inhalation, cytochrome a,a_3 was reoxidized back to baseline levels. Little or no post-hypoxia overshoot (hyperoxidation) was noted. Only when traumatic surgical preparation in animal models was accompanied by visible sludging within the cord vasculature were such hypoxia-induced redox changes absent.

Cord with Traction. There was no difference between the redox responses to hypoxia in animals without tethering and those with 1-gm traction. As the weight increased to 2 to 5 gm, however, hypoxia-

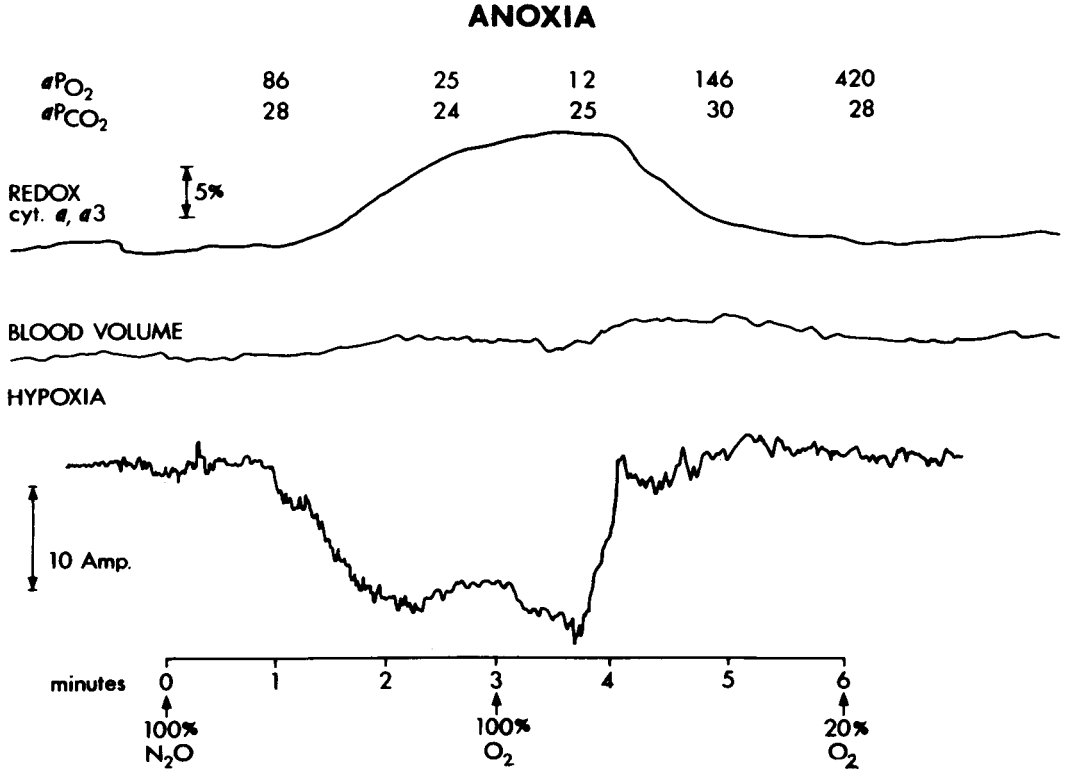

FIG. 5. Redox of cytochrome a,a_3, blood volume, and tissue O_2 availability (polarographic technique). Note the increase in reduction of cytochrome a,a_3 almost simultaneous to a decrease in O_2 tissue tension and a slight increase in blood volume.

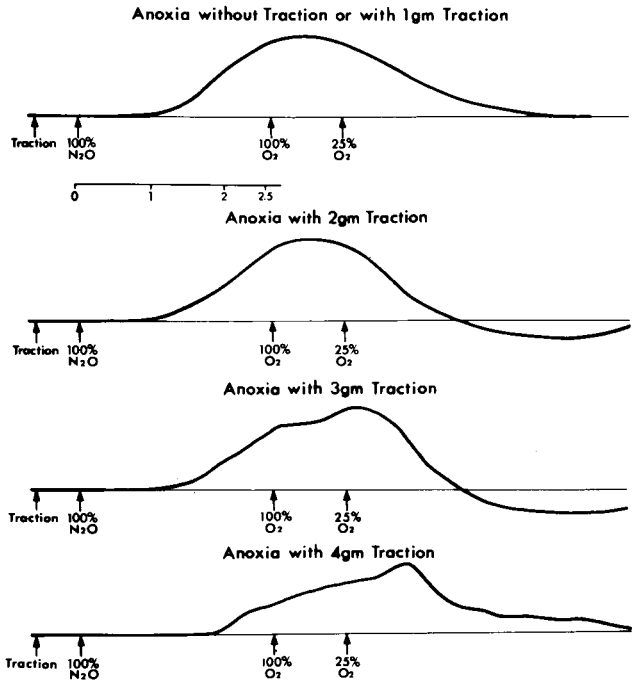

FIG. 6. Redox changes under experimental traction with various weights. Notice the delay in reduction rate in relation to the onset of hypoxia.

induced increases in the reduction level of cytochrome a,a_3 became slowed (Fig. 6). The ratio of reduction/oxidation of cytochrome a,a_3 during hypoxia under traction of 4 or 5 gm did not reach the maximum obtained under traction of 0 to 3 gm (Fig. 7).

Cord Potential

Cord without Traction. Interneuron potentials were markedly diminished in hypoxia within 2½ minutes, but they returned to normal with PaO_2 recovery. Potentials from the posterior column and from the afferent terminal diminished only slightly during anoxia, consistent with the observations of Austin and McCouch,[3] and Yamada, *et al.*[45] (Fig. 8 *upper*).

Cord with Traction. There was a significant change during anoxia noted in cords with 5-gm traction. At PaO_2 of 15 mm Hg, all the interneuron potentials disappeared. Only the potentials from the posterior column and afferent terminal remained (Fig. 8 *lower*).

Discussion

Various results have been reported in regard to surgical untethering: significant improvement,[1,19,22,24,32,47] little or no improvement,[1,42] or prevention of development or worsening of neurological deficit.[22,33,42] (But, based on cases without neurological improvement after untethering, Anderson[1] speculated that what appeared to be the cause of the tethered cord in those patients was really a dysgenesis of the cord.) In spite of increasing interest in the tethered cord, pathophysiological studies to verify the "tethered cord" syndrome and justify surgical untethering are incomplete. Three factors may account for this: 1) there have been no standardized experimental cord models of tethering that simulate the human tethered cord; 2) it has been difficult to substantiate neuronal dysfunction with biochemical changes that occur on a moment-to-moment basis in spinal cord neurons; and 3) histological studies are limited to determination of changes recognized in the later stages of dysfunction indicating irreversible damage.

Reflection spectrophotometry allows observation of metabolic functioning in the mitochondria of the cord, by *in vivo* determination of the redox changes of cytochrome a,a_3 in animal models and in patients with tethered cords. The procedure has several advantages. It does not require tissue removal, which would terminate each experiment. It does not require any cannulations of feeding arteries or draining veins that could alter cord blood flow. The method directly signals intracellular metabolism rather than requiring inferences based upon extracellular events such as polarographic oximetry.

The changes observed in cytochrome a,a_3 redox ratios and in electrical potentials indicate impaired

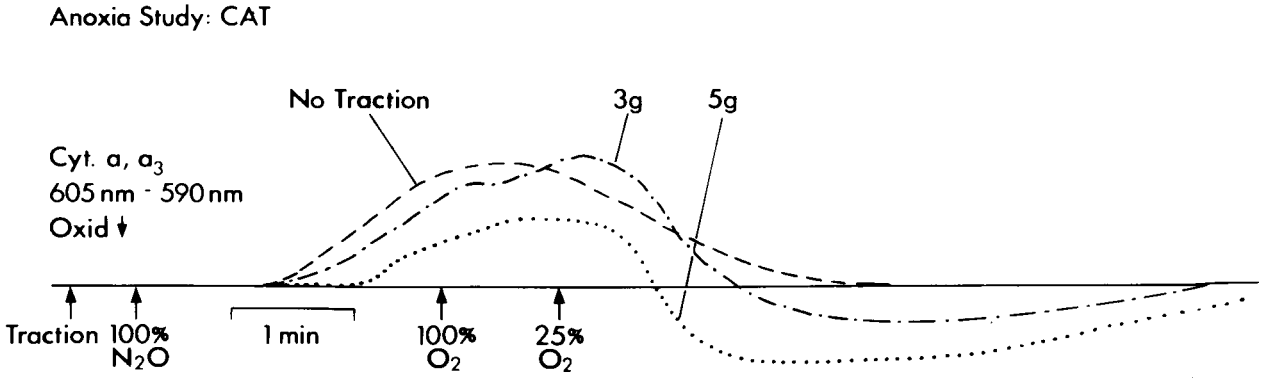

FIG. 7. Redox curves during hypoxia with and without experimental traction of 3 and 5 gm are superimposed on time line.

mitochondrial metabolic activities in cord tethering. Increasing traction weights produced an increased reduction of cytochrome a,a_3 under "resting" conditions. Increased cytochrome a,a_3 reduction also occurs in hypoxia and ischemia of the cord[45,46,48] and the cerebral cortex,[2,36] and appears to signal that cord mitochondria are approaching a condition *in vivo* analogous to that produced by anoxia in mitochondria *in vitro*.[8]

In contrast, stimulation of the posterior nerve roots results in oxidation of cytochrome a,a_3 in the cord mitochondria.[23,35] This is due to an increase in energy demands for neurons in the cord. Reduction of cytochrome a,a_3 in neuronal mitochondria can occur as a result of either decreased metabolic demand, as demonstrated with phenobarbital administration,[35] or decrease in oxygen availability.[8,23] We speculate that the mechanism involved in the tethered cord syndrome belongs to the second category. During and after traction of the experimental cord, no changes in vital signs were noted except for a slight decrease in blood pressure (10 to 20 mm Hg) during the last 15 seconds of the hypoxic study. In clinical cases, there were no changes in blood pressure and pulse rate during the hypoxic study before as well as after untethering. This indicates that possible changes in the level of anesthesia or possible pain caused by tethering are not likely to be factors in our results.

To prove that observed increases in reduced cytochrome a,a_3 were not artifacts of cord movement during tethering, responses to hypoxia were compared during tethering at low and high traction. Our study of cytochromes consists of constant observation of the reduction/oxidation ratio, and any fluctuation in the recordings is due to experimental manipulation. Cords under stress of low traction weights gave responses considerably more reduced than those under stress of higher traction (4 and 5 gm) when the cats were respired without oxygen. The human tethered cord appears to behave like the experimental cord with higher traction, and the untethered cord like the experimental cord without traction. It appears that the spinal cord, when tethered, resembles traumatized or anoxic cord with a highly reduced cytochrome a,a_3. The redox responses in the retethered cord (Fig. 3) were identical to those in the untethered cord. We believe that tethered cord mitochondria are in fact highly reduced, and untethering produces significant oxidation of cytochromes. When the mitochondria are highly reduced, which presumably is associated with decreased production of adenosine triphosphate (ATP), such metabolic impairment may result in functional deterioration of nerve cells.

The question still remains as to what caused the highly reduced state of mitochondria in the tethered cord. We believe that the mechanical effect of tethering — a stretching of the lumbosacral cord between two fixation points (one at the site of tethering and the other at the attachment of the lowest dentate ligament) — results in stretching, distortion, or kinking of arterioles, venules, and capillaries. Circulation is probably impaired, as indicated by Reigel, *et al.*,[33] in clinical cases, and by Dolan, *et al.*,[10] in the experimental distraction of the cord. Related to this is the observation of a lack of redox response of cytochrome a,a_3 demonstrated in humans previous to neurosurgical arterial anastomosis for cerebrovascular insufficiency.[2]

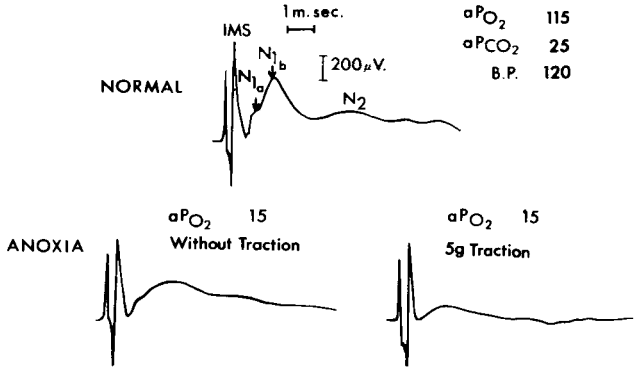

FIG. 8. *Upper:* Normal cord potentials in response to dorsal root stimulations. IMS: from the posterior column; N1a: from the afferent terminals; N1b: from the interneurons of the first order; N2: from the interneurons of the second and third orders. *Lower:* Marked change in interneuron potentials under hypoxia, especially in the cord with traction of 5 gm.

Cephalad movement and relaxation of the conus medullaris after untethering procedures have been reported at operation[19,21] and during radiological follow-up examinations.[33] Progressive neurological symptoms and signs associated with the tethered cord may well be the result of repeated metabolic insult by such stresses as further cord stretching by flexion or extension-flexion of the spine,[5,33] systemic hypoxia by strenuous exercises, or local hypoxia secondary to venous congestion caused by Valsalva maneuver or abdominal strain. Rapid deterioration of the interneuron potential in the experimental tethered cord under anoxic stress parallels impaired mitochondrial respiration, and could reflect neurological deficit in the human tethered cord. Judged by deterioration of the interneuron potentials, which are more rapid than the posterior column potential during anoxia, the nerve cells (perikarya) located in the spinal cord apparently suffer from metabolic injury earlier than the axons, which have a far lower energy requirement. This inference is supported by histological studies by Van Harreveld and Schadé[44] and Gelfan and Tarlov,[17] in which anoxia-ischemia of the spinal cord of experimental animals caused deterioration of a considerable part of the neurons, especially of the interneurons, before causing long-tract damage. Incontinence and muscle atrophy with hyporeflexia, which indicate nerve-cell damage in the lumbosacral cord, appear as early signs of the tethered cord, whereas

the long-tract signs are manifested later as muscle weakness with hyperreflexia or the Babinski sign, as in Cases 1 and 7.[19,21,47,49] Delayed latency in somatosensory evoked potentials in human cases of tethered cord was demonstrated by Reigel, *et al.*,[33] and suggests long-tract dysfunction. We speculate that untethering improves the oxidative metabolism of the cord, and this may be the cause of neurological improvement, if neuronal mitochondria are not irreversibly damaged.

Whether or not the highly reduced state of cytochromes is caused by local ischemia of the cord is not yet solved. Further simultaneous analysis of two parameters, cord metabolism and circulation, is required. Such studies could eliminate misinterpretation of metabolic function based solely on blood flow; for instance, electrophysiological activities of neurons are totally lost in an infarcted area of the brain in spite of luxury perfusion, which occurs as a response to metabolic need for the purpose of cell repair.

Summary

1. Dual wavelength reflection spectrophotometry was applied to the experimental tethered cord. Cord potential in response to the sensory root stimulation was simultaneously recorded.

2. Correlation between the electrophysiological dysfunction and metabolic impairment was established in the experimental tethered cord.

3. Human tethered cord behaves metabolically in the same manner as the experimental tethered cord.

4. The "tethered cord" is a neurological syndrome manifested by progressive neurological deficit which results from metabolic dysfunction of the lumbosacral cord neurons. Surgical untethering is the procedure of choice, not only to prevent the progress of neurological signs and symptoms, but also to ameliorate them. Untethering proved to be an effective means of improving oxidative metabolism, which corresponds to neurological improvement in humans.

References

1. Anderson FM: Occult spinal dysraphism. Diagnosis and management. **J Pediatr 73:**163–177, 1968
2. Austin G, Haugen G, LaManna J: Cortical oxidative metabolism following microanastomosis for brain ischemia, in Jöbsis FF (ed): **Oxygen and Physiological Function.** Dallas: Professional Information Library, 1977, pp 531–544
3. Austin GM, McCouch GP: Presynaptic component of intermedullary cord potential. **J Neurophysiol 18:** 441–451, 1955
4. Bassett RC: The neurologic deficit associated with lipomas of the cauda equina. **Ann Surg 131:**109–116, 1950
5. Breig A: Overstretching of and circumscribed pathological tension in the spinal cord: a basic cause of symptoms in cord disorders. **J Biomech 3:**7–9, 1970
6. Brown AW, Brierley JB: Anoxic-ischaemic cell change in rat brain. Light microscopic and fine-structural observations. **J Neurol Sci 16:**59–84, 1972
7. Bruce DA, Schut L: Spinal lipomas in infancy and childhood. **Childs Brain 5:**192–203, 1979
8. Chance B, Williams GR: The respiratory chain oxidative phosphorylation. **Adv Enzymol 17:**65–134, 1956
9. Demopoulos H, Flamm E, Seligman M, et al: Molecular pathology of lipids in CNS membranes, in Jöbsis FF (ed): **Oxygen and Physiological Function.** Dallas: Professional Information Library, 1977, pp 491–508
10. Dolan EJ, Tator CH, Transfeldt EE, et al: Effect of spinal distraction on regional spinal cord blood flow in cats. **Neurosurgery 5:**385, 1979 (Abstract)
11. Drewes LR, Gilboe DD, Betz AL: Metabolic alterations in brain during anoxic-anoxia and subsequent recovery. **Arch Neurol 29:**385–390, 1973
12. Ducker TB, Salcman M, Lucas JT, et al: Experimental spinal cord trauma, II. Blood flow, tissue oxygen, evoked potentials in both paretic and plegic monkeys. **Surg Neurol 10:**64–70, 1978
13. Eklöf B, Siesjö BK: The effect of bilateral carotid artery ligation upon the blood flow and the energy state of the rat brain. **Acta Physiol Scand 86:**155–165, 1972
14. Fitz CR, Harwood-Nash DC: The tethered conus. **Am J Roentgenol Radium Ther Nucl Med 125:**515–523, 1975
15. Garceau GJ: The filum terminale syndrome. (The cord-traction syndrome). **J Bone Joint Surg (Am) 35:** 711–716, 1953
16. Garcia JH, Lossinsky AS, Kauffman FC, et al: Neuronal ischemic injury: light microscopy, ultrastructure and biochemistry. **Acta Neuropathol 43:**85–95, 1978
17. Gelfan S, Tarlov IM: Altered neuron population in L_7 segment of dogs with experimental hind-limb rigidity. **Am J Physiol 205:**606–616, 1963
18. Goldberg ND, Passonneau JV, Lowry OH: Effects of changes in brain metabolism on the levels of citric acid cycle intermediates. **J Biol Chem 241:**3997–4003, 1966
19. Hoffman HJ, Hendrick EB, Humphreys RP: The tethered spinal cord: its protean manifestations, diagnosis and surgical correction. **Childs Brain 2:** 145–155, 1976
20. Ito T, Allen N, Yashon D: A mitochondrial lesion in experimental spinal cord trauma. **J Neurosurg 48:** 434–442, 1978
21. Jackson IJ, Thompson IM, Hooks CA, et al: Urinary incontinence in myelomeningoceles due to a tethered spinal cord and its surgical treatment. **Surg Gynecol Obstet 103:**618–624, 1956
22. James CCM, Lassman LP: Spinal dysraphism. The diagnosis and treatment of progressive lesions in spina bifida occulta. **J Bone Joint Surg (Br) 44:**828–840, 1962
23. Jöbsis FF, Keizer JH, LaManna JC, et al: Reflectance spectrophotometry of cytochrome a,a_3 *in vivo*. **J Appl Physiol 43:**858–872, 1977
24. Jones PH, Love JG: Tight filum terminale. **Arch Surg 73:**556–566, 1956
25. Jossmann PB, Fischmann J, Tedeschi CG: Congenital malformation of spinal canal with neurogenic bladder. Successful treatment by neurosurgery and transurethral bladder neck resection. **Neurology 10:**747–752, 1960
26. Kelly DL Jr, Lassiter KRL, Calogero JA, et al: Effects of local hypothermia and tissue oxygen studies in experimental paraplegia. **J Neurosurg 33:**554–563, 1970

27. Kobrine AI, Doyle TF, Martins AN: Local spinal cord blood flow in experimental traumatic myelopathy. **J Neurosurg 42**:144–149, 1975
28. Marshall LF, Welch F, Durity E, et al: Experimental cerebral oligemia and ischemia produced by intracranial hypertension. Part 3: Brain energy metabolism. **J Neurosurg 43**:323–328, 1975
29. McCouch GP, Austin GM: Site of origin and reflex behavior of postsynaptic negative potentials recorded from the spinal cord. **Yale J Biol Med 28**:372–379, 1955/6
30. Nordström C-H, Siesjö BK: Effects of phenobarbital in cerebral ischemia. Part I: Cerebral energy metabolism during pronounced incomplete ischemia. **Stroke 9**:327–335, 1978
31. Perot PL Jr: Evoked potentials. Assessment of patients with neural trauma, in McLaurin RL (ed): **Head Injuries. Second Chicago Symposium on Neural Trauma.** New York/San Francisco/London: Grune and Stratton, 1976, pp 77–79
32. Pool JL: Spinal cord and local signs secondary to occult sacral meningocele in adults. **Bull NY Acad Med 28**:655–663, 1952
33. Reigel DH, Scarff TB, Woodford J: Surgery for tethered spinal cord in myelomeningocele patients. Presented at the Annual Meeting of the American Association of Neurological Surgeons, San Francisco, California, 1976 (Paper No. 46)
34. Rogers HM, Long DM, Chou SN, et al: Lipomas of the spinal cord and cauda equina. **J Neurosurg 34**:349–354, 1971
35. Rosenthal M, LaManna J, Yamada S, et al: Oxidative metabolism, extracellular potassium and sustained potential shifts in cat spinal cord *in situ*. **Brain Res 162**: 113–127, 1979
36. Rosenthal M, Martel D, LaManna JC, et al: *In situ* studies of oxidative energy metabolism during transient cortical ischemia in cats. **Exp Neurol 50**:477–494, 1976
37. Salford LG, Plum F, Siesjö BK: Graded hypoxia-oligemia in rat brain. I. Biochemical alterations and their implications. **Arch Neurol 29**:227–233, 1973
38. Schmahl FW, Betz E, Talke H, et al: Energiereiche Phosphate und Metabolite des Energiestoffwechsels in der Grosshirnrinde der Katze. **Biochem Z 342**:518–531, 1965
39. Senter HJ, Venes JL: Loss of autoregulation and post-traumatic ischemia following experimental spinal cord trauma. **J Neurosurg 50**:198–206, 1979
40. Swanson HS, Barnett JC Jr: Intradural lipomas in children. **Pediatrics 29**:911–926, 1962
41. Thomas JE, Miller RH: Lipomatous tumors of the spinal canal. **Mayo Clin Proc 48**:393–400, 1973
42. Till K: Spinal dysraphism. A study of congenital malformations of the lower back. **J Bone Joint Surg (Br) 51**:415–422, 1969
43. Van Harreveld A: Asphyxial depolarisation in the spinal cord. **Am J Physiol 147**:669–682, 1946
44. Van Harreveld A, Schadé JP: Nerve cell destruction by asphyxiation of the spinal cord. **J Neuropathol Exp Neurol 21**:410–422, 1962
45. Yamada S, Sanders D, Haugen G: Functional and metabolic responses of the spinal cord to anoxia and asphyxia, in Austin GM (ed): **Contemporary Aspects of Cerebrovascular Disease.** Dallas: Professional Information Library, 1976, pp 239–246
46. Yamada S, Sanders D, Haugen GE, et al: Metabolic and functional changes of spinal cord in experimental ischemia. **Soc Neurosci Abstr 3**:509, 1977
47. Yamada S, Zinke D: Tethered cord syndrome. Presented at the Seventh Scientific Meeting, International Society for Pediatric Neurosurgery, September 16–19, 1979, Chicago, Illinois
48. Yamada S, Sanders D, Maeda G: Oxidative metabolism during and following spinal cord ischemia. **Neurol Res 3**:1–16, 1981
49. Yashon D, Beatty RA: Tethering of the conus medullaris within the sacrum. **J Neurol Neurosurg Psychiatry 29**:244–250, 1966
50. Yashon D, Bingham WG Jr, Friedman SJ, et al: Intracellular enzyme liberation in primate spinal cord injury. **Surg Neurol 4**:43–51, 1975
51. Yatsu FM, Moss SA: Brain lipid changes following hypoxia. **Stroke 2**:587–593, 1971

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