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Original article

Tethered Cord Syndrome：Preliminary Report of Clinical Features and Morphometric Analysis on Association of Chiari Malformation Type Ⅰ

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Abstract

Objective：Tethered cord syndrome（TCS）is an incompletely understood disorder that is characterized by symptoms attributable to downward traction of the caudal end of the spinal cord. We describe the clinical features and radiological findings of tethered cord syndrome, and the downward displacement of the hindbrain that mimics Chiari malformation type Ⅰ（CM-Ⅰ）.

Methods：This study comprised 105 patients who met the classical TCS criteria. Posterior cranial fossa size and volume were measured using reconstructed 2D computed tomography scans and magnetic resonance（MR）images. Results were compared to those in 75 year age- and sex-matched healthy control individuals. The relationships of neural and osseus structures at the craniocervical junction and thoracolumbar junction were investigated morphometrically using the MR images. For 47 patients whose symptoms had worsened or whose neurological findings had deteriorated, a section of the filum terminale was performed.

Results：CM-Ⅰ was present in 81 patients with TCS（77%）and 24 patients without CM-Ⅰ（23%）. The incidence of suboccipital headache was 58%, neck pain：55% and dizziness：43%, and nausea/vomiting 42%. The incidence of low back pain was 86%, leg pain：74% and urinary urgency or incontinence：67%. There were no significant differences in the size or volume of the posterior cranial fossa as compared to healthy control individuals. Morphometric measurements demonstrated an elongation of the brain stem（mean 6.4 mm, $p<0.001$）and a downward displacement of the medulla（mean 7.2 mm, $p<0.001$）. Symptoms and signs which were related to TCS, were improved or resolved in 31 patients（66%）, were unchanged in 14 patients（30%）, and became worse in 2 patients（4%）. Symptoms and signs which were related to CM-Ⅰ, were improved or resolved in 22 patients（47%）, unchanged in 23 patients（49%）, and became worse in 2 patients（4%）. After the section of filum terminale, morphometric measurements demonstrated reduction of the brain stem length（mean 4.3 mm, $p<0.001$）and an improvement of downward displacement of the medulla（mean 3.9 mm, $p<0.001$）.

Conclusions：TCS appeared to be a unique clinical entity that manifested an elongation and downward displacement of the hindbrain. TCS might occur as a continuum with CM-Ⅰ and may be distinguished from generic CM-Ⅰ by the absence of a small posterior cranial fossa. There was preliminary evidence that section of filum terminale section could reverse a moderate degrees of the symptoms and signs, as well as reduce the elongation and downward displacement of the brain stem.

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Key words

tethered cord syndrome, Chiari malformation, brain stem, posterior cranial fossa, filum terminale

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Table 1 Patient characteristics

Variable	Controls	Patient group (%)	
		with CM-Ⅰ	without CM-Ⅰ
No. cases	75	81 (77)	24 (23)
Age (yrs.)	16-69	16-67	19-69
mean	31.7±11.8	31.1±12.4	31.7±13.6
Sex			
male	20	20	6
female	55	61	18

Numbers in parentheses denote percentages. Mean values are expressed as ± standard deviations.
CM-Ⅰ: Chairi malfromation type Ⅰ.

Introduction

Over the past quarter century, tethered cord syndrome (TCS) has come to be recognized as a clinically important disorder in children and adults[1-8]. Anatomical abnormalities of the filum terminale are thought to be due to disturbances in the retrogressive differentiation during secondary neurulation that contribute to fibrofatty infiltration and reduced viscoelasticity[4,5,8]. The pathogenesis of the syndrome is attributed to downward traction on the conus medullaris by a tight filum terminale that results in a stretching of the neuronal elements[1,9,10], impaired regional blood flow[11-13], and a decrease of oxidative metabolism[14]. The symptomatology includes bladder and bowel disturbances, back and leg pain, lower extremity weakness, and segmental sensory disturbances[1,5]. Traditional TCS radiographic criteria of TCS have required evidence of a short, thick, or fatty filum terminale and a low-lying conus medullaris with its tip positioned at or below L1/2 or the endplate of the L2 vertebral body[15-17]. There is no scientific evidence, which actually proves a connection between spinal cord tethering and the observed symptoms.

Early in the current investigation, we observed an association of TCS-like symptoms, cerebellar prolaps, and persistent tonsillar herniation in patients with Chiari malformation typeⅠ (CM-Ⅰ) in whom symptoms had recurred following apparently successful decompression surgery. Conversely, CM-Ⅰ has been reported only rarely in association with lesions that tethers the spinal cord[18-22]. We could therefore expect that a morphometrical examination of the relationship of tonsillar herniation and TCS could provide us with some clues for resolving the pathogenesis of TCS.

To examine a possible relationship between TCS and tonsillar herniation, we analyzed a prospectively accrued cohort of patients with TCS combined with CM-Ⅰ. Clinical and radiographic findings were supplemented by morphometric measurements of the brain, posterior cranial fossa and spinal cord.

Clinical material and methods

1 Study population

The study population consisted of 105 patients with TCS (following criteria) who were evaluated consecutively between January 2006 and August 2007. There were 79 females and 26 males who ranged in age from 16-69 years (mean age 31.3±12.7 years [±SD]) (**Table 1**). Patients excluded only those 15 years of age and younger, or older than 69 years were exculuded from this study to eliminate any possible age-related changes of the skull and brain.

2 Assessment

1. Diagnostic findings

The diagnosis of TCS was based on the following nonspecific but generally accepted symptoms and signs: urinary dysfunction (including incontinence, urgency, sensory loss, incomplete emptying of the bladder), bowel incontinence, low back pain, leg and foot pain, numbness of the soles of the feet, gait disturbance, leg weakness, atrophy of the calf muscles, loss of deep tendon reflexes in the lower extremities, thoracolumbar scoliosis, equinovarus or equinovalgus deformities of the feet, and spinal dysraphism[1,5]. Traditional radiographic findings included evidence of a low-lying conus medullaris below L1/2 and fatty infiltration or thickening (>2.0 mm diameter) of the filum terminale[3,8,15]. In this study, we extended the radiographic and symptomatic criteria to include patients with a conus medullaris positioned below L1/2 and the absence of fatty infiltration or thickening of the filum terminale[15,17,23], if those patients evidenced classical symptomatology and met 4 or more of the following criteria:

1) neurogenic bladder confirmed by urodynamic testing

2) positive toe walking test (relief of symptoms including low back pain and urinary urgency)

3) positive heel walking test (increase of symptoms including low back pain and urinary urgency)

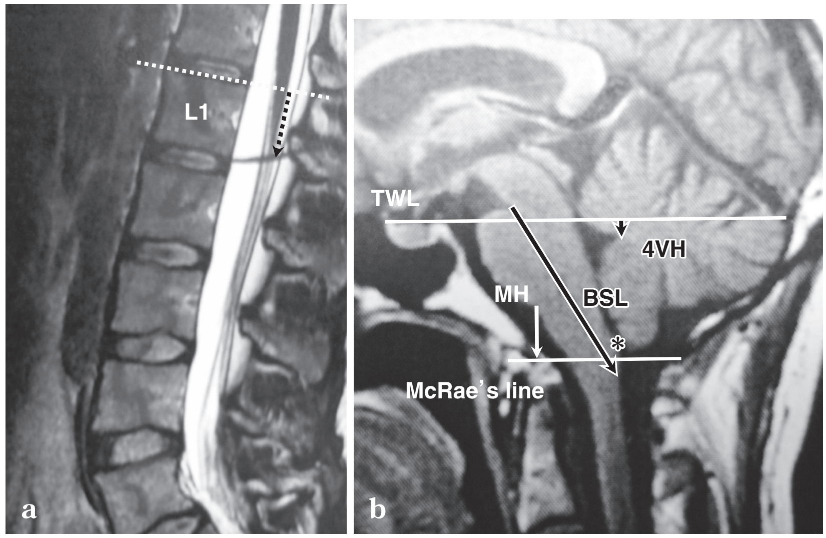

Fig. 1 Lines and measurement intervals for assessing neural and osseus structures at the thoracolumbar junction and craniocervical junction in a 25-year-old healthy control female

a：a midsagittal T2 weighted MR image of the lumbar spine shows the position of the conus medullaris which was measured as the distance between the upper endplate of L1（upper line）and tip of the conus medullaris.

b：a midsagittal T1 weighted MR image of the posterior cranial fossa shows Twining's line（TWL）between the internal occipital protuberance and tuberculum sellae and McRae's line between the opisthion and basion. BSL：axial length of brain stem was measured from the mesencephalic-pontine junction to the posterior-inferior margin of the gracile tubercle（asterisk）, MH：height of the medulla was measured as the distance between the pontomedullary junction and McRae's line, 4VH：height of the fourth ventricle was measured as the distance between line TWL and the posterior apex of fourth ventricle.

*：gracile tubercle.

4）terminal thoracic syringomyelia（T5 or below）in the absence of a rostral cavity[2,24)]

5）thoracolumbar scoliosis[25-28)].

Questionnaires were developed to elicit patient' family history information. All patients underwent a physical examination, complete neurological examination, whole-neuraxis MR imaging, and CT of the head with 2D and 3D reconstruction. The clinical and radiographic imaging criteria for establishing the diagnosis of CM-Ⅰ have been described previously[29,30)].

2. Morphometric analysis of the thoracolumbar junction and craniocervical junction

Neural and osseus relationships at the thoracolumbar junction were investigated using MR-imaging. The position of the conus medullaris was assessed on sagittal MR images after counting the number of lumbar vertebral bodies on plain X-rays. The position of the conus medullaris was measured as the distance between the plane of the upper endplate of L1 and the tip of the conus on midsagittal T-2 weighted images（**Fig. 1 a**）.

Brain and bone structures comprising the posterior cranial fossa were investigated using T1 weighted MR images in the midsagittal plane（**Fig. 1 b**）. The cervicomedullary junction was identified radiologically by the inferior margin of the gracile tubercle[31)]. We assessed brain and bone relationships using new measurements developed by us. The axial length of the brain stem was measured from the mesencephalic-pontine junction to the posterior-inferior margin of the gracile tubercle[32)]. We could not measure the axial length of the brain stem in 17 cases, because the inferior margins of the gracile tubercle in those cases were unclear. We measured the height of the medulla from the pontomedullary junction to the foramen magnum along a line drawn perpendicular to McRae's line. The height of the fourth ventricle was measured as the perpendicular distance between Twining's line and

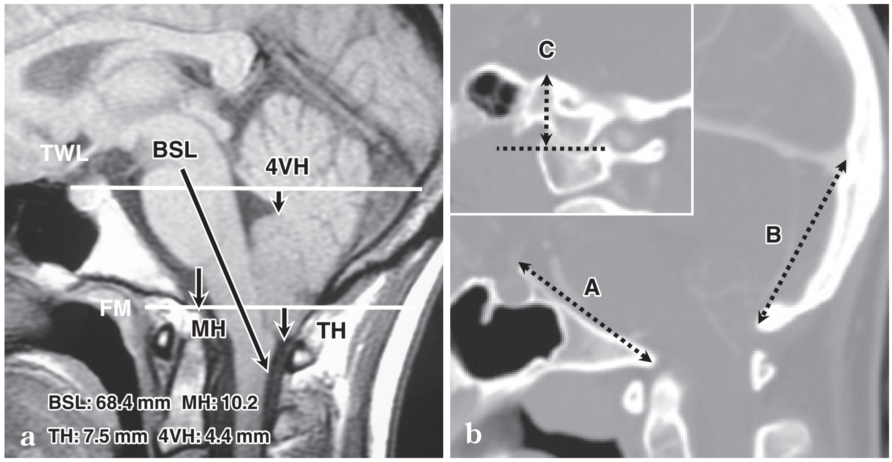

Fig. 2 Morphometric assessments of the craniocervila junction and posterior cranial fossa in a 28-year-old female with CM-Ⅰ/TCS

a：a midsagittal T-1 weighted MR image shows elongation of the brain stem（BSL＝68.4 mm), herniation of the cerebellar tonsils（TH＝7.5 mm), and downward displacement of the brain stem（MH＝10.2 mm). FM：McRae's line.

b：a midsaggital and parasagittal（upper）reconstructed 2D-CT images show normal occipital bone size. A：axial length of clivus（distance between the top of the dorsum sellae and basion). B：axial length of the supraoccipút（distance between the center of the internal occipital protuberance and opisthion). C：axial length of the exocciput（distance between the top of the jugular tubercle and the bottom line of the occipital condyle).

the posterior apex of the fourth ventricle.

3. Morphometric and volumetric analysis of the posterior cranial fossa

Using reconstructed 2D CT, the size of the occipital bone was determined by measuring its enchondral components（exocciput, basiocciput, and supraocciput）which enclose the posterior cranial fossa[33]. We measured the axial length of the clivus（basiocciput）from the top of the dorsum sellae to the basion；the axial length of the supraocciput from the center of the internal occipital protuberance to the opisthion；and the axial length of the occipital condyle（exocciput）from the top of the jugular tubercle to the bottom of the occipital condyle[33]（**Fig. 2**).

The posterior cranial fossa volume, brain volume in the posterior cranial fossa, and cerebrospinal fluid（CSF）volume were calculated on reconstructed 2D CT images using the Cavalieri method[30,34,35] or radiographic analysis software（Image J, NIH, MD, USA)[36]. The posterior cranial fossa was defined as the nearly spherical space bounded by the tentorium, occipital bone, clivus, and petrous bone.

3 Surgical treatment and follow-up

For the 47 patients with neurological abnormalities, which had been deteriorating, a section of filum terminale was performed. All of these patients have been followed in an outpatient clinic by us. Checking of clinical symptoms and neurological findings was repeated 12-31 months postoperatively（mean 18.5 months±5.0 months [±SD]).

4 Statistical analyses

Statistical analyses of clinical data were performed with SPSS for Windows（version 15.0；SPSS Inc., Chicago, IL). Demographic differences between patients and healthy control individuals were tested with nonparametric Mann-Whitney U-test and parametric Student's *t*-test. Significance was indicated by a two-tailed probability value of less than 0.01.

Results

1 Clinical presentation of patients

The diagnostic findings in patients are shown in **Table 2**. The incidence of suboccipital headache was 61/105（58%), neck pain：58/105（55%), dizziness：45/105（43%), nausea/vomiting：44/105（42%), upper extremity motor weakness：33/105（31%）and upper extremity pain or numbness : 30/105 (29%). The incidence of low back pain was 90/105 (86%), leg pain : 78/105 (74%), urinary urgency or incontinence : 71/105 (68%), lower extremity numbness : 70/105 (67%), lower extremity motor weakness : 48/105 (46%), loss of deep tendon reflex : 44/105 (42%), muscle atrophy at lower extremity : 20/105 (19%), peps cavus deformity : 5/105 (5%), bowel disturbance : 64/105 (61%), numbness of pelvic area : 62/105 (59%), positive filum terminale traction test : 77/105 (73%).

The incidence of CM-Ⅰ was 81/105 (77%), terminal syringomyelia : 23/105 (22%). Thoracolumbar scoliosis, defined as trunk rotation equal to or greater than a Cobb angle of 15 degrees[26,27], was found in 20 patients (19%). Also, lipomyelomeningocele was present in 7 cases (6%), while Neurogenic bladder was observed in 51 patients (49%).

2 Morphometric and volumetric analysis of the posterior cranial fossa, the thoracolumbar junction and craniocervical junction

As shown in **Table 3**, there were no significant differences in occipital bone size, the volume of the posterior cranial fossa, and CSF volume between in patients with CM-Ⅰ or without CM-Ⅰ and healthy control individuals. The axial length of the brain stem was greater in patients with CM-Ⅰ and without CM-Ⅰ as compared to healthy control individuals. The medullary height was reduced in the patients with CM-Ⅰ and without CM-Ⅰ as compared to healthy control individuals. The distance of the 4^{th} ventricle below Twining's line in the patients with CM-Ⅰ was increased as compared to healthy control individuals (**Fig. 2**). There were no significant differences in the axial length of the brain stem and medullary height between patients with CM-Ⅰ and without CM-Ⅰ. Reduction of the medullary height in patients with CM-Ⅰ or without CM-Ⅰ was taken as evidence of downward displacement of the brain stem in the absence of a short clivus. Increases in the distance of the 4^{th} ventricle below Twining's line in patients with CM-Ⅰ was also taken as evidence of downward displacement of the cerebellum in the absence of a short supraocciput.

3 Surgical outcome

Symptoms and signs which are related to TCS, improved or resolved in 31 patients (66%), remained unchanged in 14 patients (30%), and became worse in 2 patients (4%). Symptoms and signs which are related to CM-Ⅰ, improved or resolved in 22 patients (47%), remained unchanged in 23 patients (49%), and became worse in 2 patients (4%, **Table 4**). After section of filum terminale, morphometric measurements demonstrated a reduction of the brain stem length (mean 4.3 mm, $p<0.001$), with improvement of the downward displacement of the hindbrain (mean 3.9 mm, $p<0.001$), and a rising of the conus medullaris (mean 6.2 mm, $p<0.001$, **Table 5**).

Table 2 Clinical presentation of patients with TCS

Variables	
Total no. patients	105
Symptoms and signs related to CM-Ⅰ	
suboccipital headache	61 (58)
neck pain	58 (55)
dizziness	45 (43)
nausea/vomitting	44 (42)
motor weakness of upper extremity	33 (31)
upper extremity pain or numbness	30 (29)
Symptoms and signs related to TCS	
low back pain	90 (86)
leg pain	78 (74)
urinary urgency or incontinence	71 (68)
lower extremity numbness	70 (67)
lower extremity motor weakness	48 (46)
loss of deep tendon reflex	44 (42)
musclar atrophy	20 (19)
pes cavus deformity	5 (5)
bowel disturbances	64 (61)
numbness of pelvic area	62 (59)
positive FT traction tests*	77 (73)
Radiological findings	
CM-Ⅰ	81 (77)
terminal syrinx (below T5)	23 (22)
thoracolumbar scoliosis	20 (19)
lipomyelomeningocele	7 (7)
Neurogenic bladder (urodynamics)	51 (49)

Numbers in parentheses denote percentages.
TCS : tethered cord syndrome, CM-Ⅰ = Chiari malformation type Ⅰ, FT : filum terminale.
* : Toe walking and heal walking test.

Discussion

1 Clinical features of TCS

The controversial status of TCS posed a number of challenges for the current study. Because the diagnosis is inexact and often subjective, we relied on generally accepted clinical and radiographic criteria[1,5,6]. Clinical features were similar to those presented in other reports[1–5,7,24,28].

Table 3 Comparison of morphometric measurements and volumetric calculations

Variable	Normal controls	With CM-Ⅰ
Total no. patients	75	81 (77)
Brain structures		
BSL (mm)	51.6±2.32	58.5±2.58†
MH (mm)	18.8±3.17	11.4±2.87‡
TH (mm)	−3.4±2.71	9.1±2.45
4VH* (mm)	4.2±3.14	8.2±2.41†
Position of conus medullaris (mm)	18.2±8.52	37.2±12.11
Occipital bone size		
axial length of clivus (mm)	47.0±2.17	45.4±2.56
axial length of supraocciput (mm)	47.7±2.52	46.9±2.58
axial length (right) of occipital condyle (mm)	24.1±1.65	23.8±2.64
axial length (left) of occipital condyle (mm)	24.3±1.54	23.7±2.72
Volumetric analysis		
PCFV (ml)	189.1±7.84	183.7±8.67
PFBV (ml)	151.8±3.14	152.5±4.72
CSF space (ml)	37.2±5.57	31.2±6,27

Mean values are expressed as ± standard deviations.
CM-Ⅰ: Chiari malformation type Ⅰ, BSL: brain stem length, MH: medullary height, TH: tonsillar herniation, 4VH*: fourth ventricle height, PCFV: posterior cranial fossa volume, PFBV: posterior fossa brain volume, CSF: cerebrospinal fluid.
*: Distance between Twining's line and posterior apex of the fourth ventricle.
†: significant differences (larger) as compared to normal controls ($p<0.001$).
‡: significant differences (smaller) as compared to normal controls ($p<0.001$).

Table 4 Surgical outcome in patients undergoing SFT

Variables	
Total no. patients	47
Symptoms and signs of CM-Ⅰ	
resolved	2 (4)
improved	20 (43)
unchanged	23 (49)
worse	2 (4)
Symptoms and signs of TCS	
resolved	10 (21)
improved	21 (45)
unchanged	14 (30)
worse	2 (4)
Mean follow up (months)	18.5±5.04

Numbers in parentheses denote persentages. Mean values expressed as±standard deviations.
SFT: section of filum terminale, CM-Ⅰ: Chiari malformation type Ⅰ, TCS: tethered cord syndrome.

Table 5 Comparison before and after section filum terminale

Variable	with CM-Ⅰ	without CM-Ⅰ
total no. patients	30	17
brain structures		
Reduction of BSL (mm)	5.4±2.91†	2.4±2.14‡
Increasing of MH (mm)	4.4±3.12†	3.1±2.97‡
Reduction of TH (mm)	3.8±2.28†	—
Reduction of 4VH* (mm)	3.3±2.64‡	—
position of conus medullaris (mm)	6.4±3.34†	5.8±3.11†

Mean value are expressed as±standard deviations.
CM-Ⅰ: Chiari malformation type Ⅰ, TCS: tethered cord syndrome, BSL: brain stem length, MH: medullary height, TH: tonsillar herniation, 4VH*: fourth ventricle height.
*: Distance between Twining's line and posterior apex of fourth ventricle.
†: significant differences as compared to the data of pre-section filum terminale ($p<0.001$).
‡: significant differences as compared to the data of pre-section filum terminale ($p<0.01$).

Rates of improvement of symptoms and signs, which were related to TCS, were also similar to those of the other reports[1,3,5,7,23]. These results suggested that our cohort was similar to the cohort used in the other reports. Symptoms and signs, which were related to CM-Ⅰ, also improved in half of our patients. These results let us guess at the etiological relationship between TCS and CM-Ⅰ.

2 Morphometric analyses of thoracolumbar junction and craniocervical junction in TCS

We developed a set of quantitative morphometric measurements for assessing the position of the conus medullaris, the length of the pons and medulla oblongata, the position of the ponto-mesencephalic and ponto-medullary junctions referable to the foramen magnum,

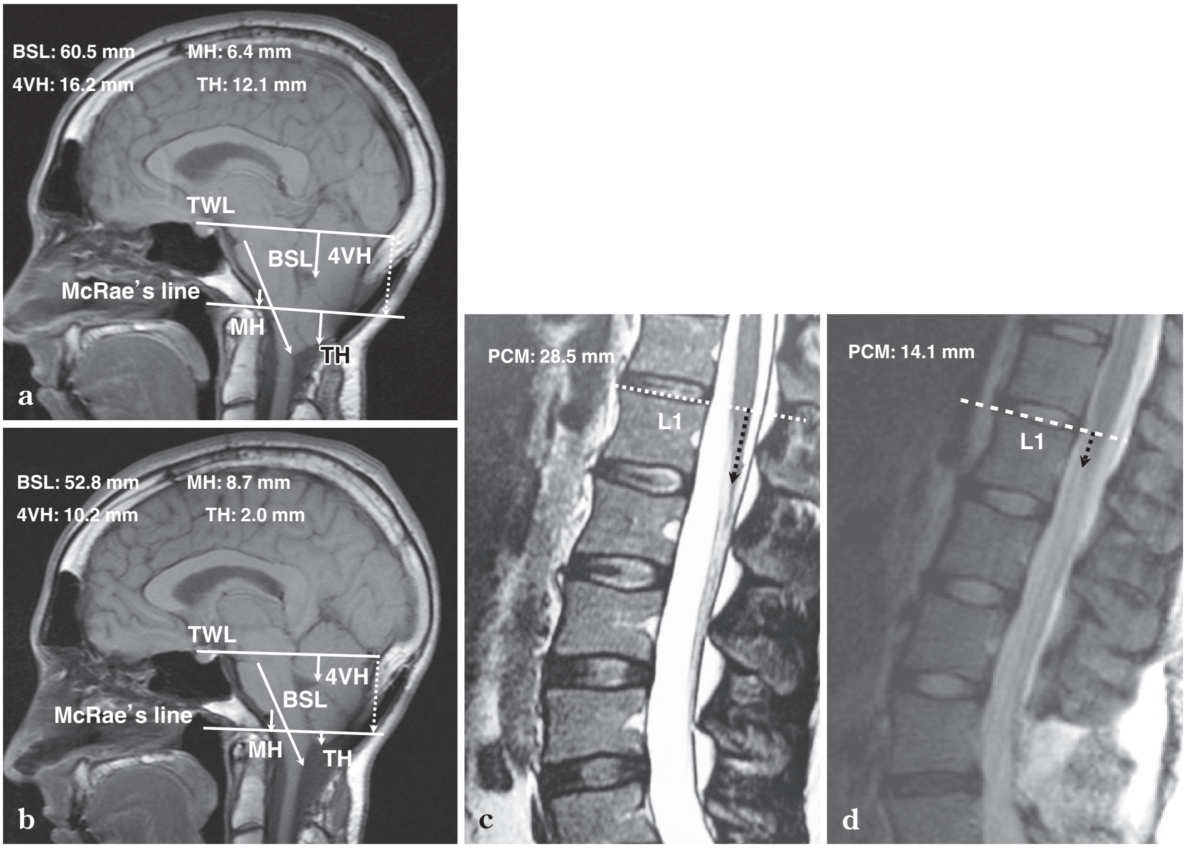

Fig. 3 Morphometric assessments of the craniocervical junction and thoracolumbar junction in a 37-year-old female with TCS/CM-Ⅰ before and after section filum terminale

a：a midsagittal MR image after large posterior fossa decompression, in spite of cranioplasty performed, the cerebellum and brain stem had prolapse（BSL：60.5 mm, MH：6.4 mm, 4VH：16.2 mm, TH：12.1 mm）. For purposes of redrawing McRae's line after suboccipital craniectomy, the length of a line perpendicular to Twining's line and extending from the internal occipital protuberance to McRae's line was measured on preoperative films（dotted line）.

b：a midsagittal MR image of the head after section of filum terminale in the same patient, the length of the brain stem decreased and the brain stem and cerebellum rose upward（BSL：52.8 mm, MH：8.7 mm, 4VH：10.2 mm, TH：2.0 mm）.

c：a midsagittal MR image of the lumbar spine before section of filum terminale in the same patient；the position of the conus medullaris was 28.5 mm. PCM＝position of the conus medullaris.

d：a midsagittal MR image of the lumbar spine after section of filum terminale in the same patient, the position of the conus medullaris was 14.1 mm. The position of the conus medullaris moved ventrally. PCM＝position of the conus medullaris.

and the position of the 4^{th} ventricle referable to Twining's line. The size and volume of the posterior cranial fossa were assessed using established methodology[29,30,33,34,36]. These morphometric measurements suggested that the elongation of the brain stem and downward displacement of the hindbrain in tethered spinal cord as the evidences which were induced from the data showing the increasing length of the pons and medulla oblongata, and the lowering of the position of the pontomedullary junction and fourth ventricle position in tethered spinal cord. The occipital bone size and the volume of the posterior cranial fossa were normal.

The etiology of elongation of the brain stem and cerebellar tonsils by traction was certified by physiological experiment[37]. The authors can show the circumstantial evidences, which demonstrates traction for the hindbrain and tethered spinal cord. The authors experienced many cases who had cerebellar prolapse after decompression surgery（**Fig. 3 a**）. After section filum terminale, the length of the brain stem decreased and the brain stem and cerebellum went up（**Table 5**, **Fig. 3 a**, **b**), and the conus medullaris went up as well（**Table 5**, **Fig. 3 c**, **d**）. Together these observations sugges that the brain stem was pulled down, and that elongation of the brain stem was reversible by sectioning of filum terminale, which relieves tethered spinal cord. According to these theoretical support and empirical evidences, the elongation of the brain stem and downward displacement of the brain stem and cerebellum might be scientific criteria suggesting traction as one of causes of tonsillar herniation.

3 The relationship of TCS and CM-Ⅰ

In discussing the pathogenesis of CM-Ⅰ, there is a general consensus that the disorder is caused by an underdevelopment of the posterior cranial fossa where by overcrowding of the hindbrain those results in downward displacement and herniation of the cerebellar tonsils[30,31,33,38]. In patients with TCS/tonsillar herniation, morphometric measurements of the posterior cranial fossa revealed a normal size and volume of the posterior cranial fossa. These findings exclude overcrowding of the hindbrain as a mechanism for downward displacement of the cerebellar tonsils and identify TCS/tonsillar herniation as a distinct clinical entity that can be differentiated from generic CM-Ⅰ.

Unfortunately, there are no experimental models that test the cord-traction theory directly. At this point the authors have to rely on circumstantial evidences. To date, lesions that tether the spinal cord have been reported only occasionally in association with CM-Ⅰ including ten patients with lipomyelomeningocele[19,21,22], four patients with a "tight" filum terminale[20], and a 3 year-old-female with a thick fatty filum termianle who exhibited increasing tonsillar herniation with somatic growth[18]. Besides these previous reports, in this report, based on the morphological characteristics of the posterior cranial fossa in a patient with TCS associated with CM-Ⅰ, the authors suggested that traction by tethered spinal cord might be one of possibilities, which caused tonsillar herniation.

Conclusions

Besides a low-lying conus medullaris as one of definitions of TCS, TCS diagnosis was made by morphometric evidence of brain stem elongation and downward displacement of the brain stem. In patients with CM-Ⅰ, downward displacement of the cerebellum was also demonstrated. Elongation and downward displacement of the hindbrain were reversible by releasing of spinal cord tethering. In this report, the morphological characteristics of the posterior cranial fossa in those patients suggested that traction caused by their tethered spinal cords might be one of possibilities, which caused tonsillar herniation.

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Ethics approval

Provided by Institutional Review Board (IRB) of the North Shore-Long Island Jewish Health System.

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