Phase-Contrast Magnetic Resonance Imaging Study on Cord Motion in Patients with Spinal Dysraphism: Comparison with Healthy Subjects

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Key Words: phase-contrast magnetic resonance imaging, cord motion, healthy subjects, spinal dysraphism

Summary

Cord motion at the cervical cord (C-3) level was measured with phase-contrast magnetic resonance imaging (MRI) in 39 healthy young subjects and 34 age-matched patients with spinal dysraphism.

Cord velocity curves (composed of waves I, II, and III) were made in both sagittal images and transverse images and classified into 3 types. The measurement in the sagittal images were more reproducible than that in the transverse images.

In healthy subjects, the mean cord velocity of wave I was 0.49±0.11 cm/s in the sagittal image. In the subgroup of patients with spinal dysraphism showing stable clinical courses, cord velocity was comparable to that in the healthy subjects. Patients of the subgroup with symptomatic aggravation showed a significant decrease in cord velocity in wave I, and a characteristic pattern in the cord velocity curve: the velocity change (wave I) was small. This decrease in cord velocity was thought to be due mainly to cord tethering. The measurement of cord motion with phase-contrast MRI could give objective and quantitative information about cord motion and tethering associated with spinal dysraphism.
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Introduction

In phase-contrast magnetic resonance imaging (MRI), bipolar magnetic field gradients are applied to moving spins, and the resultant phase contrasts are utilized to measure the velocity and direction of the flow. This technique has increasingly been used in clinical practice such as in MR angiography, cerebrospinal fluid (CSF) circulation dynamics (1,2), brain motion study (3-5), and cerebral blood flow measurement (6,7). However, only a few authors have measured spinal cord motion by using phase-contrast MRI techniques. Even in healthy persons, cord motion has not fully been studied with such techniques.

Tethered cord syndrome (TCS) occurring in patients with spinal dysraphism has been accepted as an established concept based on a large number of clinical reports and experimental studies (8-11). Early diagnosis and early treatment have been recommended and produced excellent therapeutic results (12,13). However, it is difficult in clinical practice to detect symptomatic aggravation in the early stages of the disease. Especially in patients who have undergone surgery for myelomeningoceles or spinal lipomas in their neonatal and infantile years, early detection of TCS is difficult because they have already suffered neurological symptoms even in the absence of TCS, and early detection cannot be made by using ordinary MRI techniques because most of such patients have a low-set conus medullaris (14,15). At present, no objective or quantitative methods are available to determine the presence, severity, or time-course changes of retethering (13). Real-time ultrasonography (16-18), somatosensory evoked potential, electromyogram (19-21), urodynamic test (22,23), and phase-contrast MRI (24-27) may be useful for this purpose, but satisfactory reports on their clinical use have not been available to date.

We took advantage of phase-contrast MRI techniques to measure cord motion for the purpose of early diagnosis of TCS. We first analyzed cord velocity curves, classified their wave components, and defined the patterns of cord motion in healthy subjects. Then, we assessed the clinical usefulness of this technique by comparing long-term findings between patients with spinal dysraphism and healthy subjects.

Materials and Methods

The subjects were a total of 73 individuals, consisting of 34 patients with spinal dysraphism and 39 healthy subjects at 10 years of age or more. The patient group consisted of 24 who had undergone myelomeningocele surgery, 7 who had
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undergone spinal lipoma surgery and 3 non-surgical cases. They were aged 10 to 39 (mean 18) at the time of our first examination, and consisted of 17 males and 17 females. Out of the 34 patients, 27 (79%) had shown no symptomatic change to date, but the remaining 7 (21%) had experienced symptomatic aggravation. They included 2 cases of past myelomeningocele surgery, 3 cases of past spinal lipoma surgery, and 2 non-surgical patients. The symptoms showing aggravation were motor dysfunction in 4 cases, pain in 3, worsened deformity in 3, and urinary dysfunction in 1. The healthy subjects were aged 16 to 32 (mean 22), and consisted of 20 males and 19 females. This age distribution was similar to that of the patients with spinal dysraphism.

Cord motion at the cervical cord (C-3) level was measured as cord velocity in the rostrocaudal direction using sagittal and transverse images obtained with phase-contrast MRI: plus indicates the caudal direction, and minus the rostral direction. In each image, 3 regions of interest (ROI) were defined near at the C-3 level. Each ROI had a diameter of one-half to one-third of the cord diameter. The velocity was measured at the center region of the cord. The phase-contrast MRI systems used were Gyroscan ACS II 1.5T (Philips) and Visart 1.5T (Toshiba). For Gyroscan ACS II, a 2D-cine phase contrast technique was used, and images were reconstructed by using a retrogating procedure while each cardiac cycle was divided into 15 phases. The following imaging parameters were used: repetition time 19 ms, echo time 12 ms, flip angle 15 degrees, section thickness 5 mm, image matrix 128×128, field of view 150 mm, and velocity encoding 100 mm/s in the rostrocaudal direction. For Visart 1.5 T, the same 2D-cine phase contrast technique was used. In order to reconstruct an image, triggering began 2 ms after the R wave of the electrocardiogram and continued thereafter at 30-ms intervals to acquire a total of 21 single section images (2 ms to 602 ms). The imaging parameters used were: repetition time 30 ms, echo time 15 ms, flip angle 15 degrees, section thickness 5 mm, image matrix 128×256, field of view 150 mm, and velocity encoding 50 mm/s in the rostrocaudal direction.

Cord velocity was measured in relation to the complication of hydrocephalus in patients with past myelomeningocele surgery. We examined Evans' index (EI) which were defined as follows: EI=B/A, A = the greatest transverse diameter of cerebrum, B = the greatest distance between the anterior horns, on follow-up computed tomography (CT).

We also compared the pre-operative and post-operative (within 4 months) cord motion in the 4 infants with spinal lipoma below 1 year of age under the sedation using the intravenous injection of midazolam and ketamine hydrochloride.
Results

Cord velocity in the rostrocaudal direction at the C-3 level was studied in sagittal and transverse images obtained from 39 healthy subjects. The cord velocity was measured in the sagittal images in 36 of the 39 cases, in the transverse images in 32 cases, and in both images in 29 cases. Three typical cord velocity curves for both sagittal and transverse images are schematically shown in Fig. 1. In one of the curves classified as type I, the velocity measured through image acquisitions gated to the R wave increased first in the caudal direction to its peak (wave I), and then changed its direction to reach its rostral peak (wave II). After a temporary plateau, the velocity became directed again toward the caudal direction (wave III). In the type II pattern, the velocity increased first in the caudal direction (wave I), and then turned its direction inversely to reach its rostral peak (wave II). After a temporary decrease, the velocity increased again in the rostral direction (thus forming a biphasic pattern in the rostral direction), and then turned to the caudal direction. In the type III pattern, waves I and II were followed by another rostral peak which was higher than the first one, and then the velocity became directed to the caudal direction. Among the 36 healthy cases whose cord

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Fig. 1. Cord velocity curves at the cervical cord (C-3) level in healthy subjects. Cord velocity curve is composed of 3 component waves and classified into 3 types. Type I is typical among healthy subjects.
velocity in the rostrocaudal direction was studied in the sagittal images, 24 (67\%) showed type I patterns of velocity, 9 (25\%) showed type II, and 3 (8\%) showed type III. Among the 32 healthy cases whose cord velocity was studied in the transverse images, 25 (78\%) showed type I, 3 (9\%) showed type II, and 4 (13\%) showed type III patterns. The delay time from the R wave in the sagittal images was 101±26 ms for wave I, 182±32 ms for wave II. It was 102±27 ms and 180±26 ms, respectively, in the transverse images (Table 1). As shown in Table 1, the mean cord velocity in wave I was 0.49±0.11 cm/s (0.2 to 0.8) in the sagittal images, and 0.47±0.21 cm/s (0.1 to 0.9) in the transverse images, showing a rough

Table 1  The mean cord velocity is roughly consistent between the sagittal and transverse images (especially in wave I).

<table>
<thead>
<tr>
<th></th>
<th>Wave I</th>
<th>Wave II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>Delay time</td>
<td>Velocity</td>
</tr>
<tr>
<td></td>
<td>from R wave</td>
<td>from R wave</td>
</tr>
<tr>
<td>Sagittal</td>
<td>(cm/s)</td>
<td>(msec)</td>
</tr>
<tr>
<td></td>
<td>0.49 ± 0.11</td>
<td>101 ± 26</td>
</tr>
<tr>
<td>(n = 36)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>0.47 ± 0.21</td>
<td>102 ± 27</td>
</tr>
<tr>
<td>(n = 32)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( + : caudal direction</td>
<td>- : rostral direction)</td>
<td></td>
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</tbody>
</table>

consistency although there was a slightly larger variance among the values obtained from the transverse images (Fig. 2). In wave II, the mean cord velocity was −0.14±0.28 cm/s (−0.8 to −0.26) in sagittal images, and −0.30±0.3 cm/s (−0.9 to −0.23).

A representative case is shown in Fig. 3. This was obtained from a 19-year-old woman. Her cord velocity curves were classified as type I in both the sagittal and transverse images. In the former image, cord velocity was 0.4 cm/s for wave I and −0.7 cm/s for wave II, and the delay time from the R wave was 122 ms and 182 ms, respectively. In the latter image, cord velocity was 0.4 cm/s and −0.8 cm/s, respectively, and the delay time from the R wave was 122 ms and 182 ms,
Fig. 2. Cord velocity in wave I in healthy subjects. Cord velocity in wave I in the sagittal image (Left) and in the transverse image (Right), showing a rough consistency with a slightly larger variance among the values obtained from the transverse images.

respectively. The values were consistent in the sagittal and transverse images. Her pattern was considered typical among the healthy subjects.

All of the 34 patients with spinal dysraphism were studied for the rostrocaudal cord velocity at the C-3 level in the sagittal images, and 32 among them in the transverse images. Cord velocity curves obtained from the sagittal images were classified as type I in 24 of the 34 cases (70%), type II in 5 (15%), and type III in another 5 (15%). In the transverse images, type I pattern appeared in 24 of the 32 cases (75%), type II in 5 (16%), and type III in 3 (9%). These values were comparable to those from healthy subjects. Clinical courses of these patients were
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Fig. 3. Cord velocity curve in healthy subject (a 19-year old woman). Her cord velocity curves are classified as type I in both the sagittal and transverse image.

studied in relation to their cord velocity (especially in wave I). The patients were divided into 2 subgroups: 27 without symptomatic aggravation (stable subgroup), and 7 with symptomatic aggravation (deteriorating subgroup). In the sagittal images, cord velocity in wave I in the stable subgroup and healthy subjects was comparable, it was significantly lower in the deteriorating subgroup than in the healthy subjects (Fig. 4, Table 2). Cord velocity in wave I in the deteriorating subgroup was also significantly lower than that in the stable subgroup. The deteriorating subgroup showed a characteristic pattern in the cord velocity curve as well: the velocity change in the caudal direction (wave 1) was small as shown in Fig. 5. The delay time from the R wave was not markedly different between
Fig. 4. Cord velocity (wave I) in patients with spinal dysraphism (stable group and deteriorating group). Left: sagittal image. Right: transverse image. Cord velocity (wave I) in the stable group and healthy subjects is comparable. Cord velocity (wave I) in the deteriorating group is significantly lower (p<0.01) than that in healthy subjects in both sagittal and transverse images and is also significantly lower than in the stable group. Open circles: spinal lipoma, Closed circles: myelomeningocele, Asterisks: non-surgical cases.

Table 2 Cord velocity (wave I) in the deteriorating group is significantly lower than that in healthy subjects and in stable group, in both images.
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**Cord velocity curve**

![Cord velocity curve](image)

Fig. 5. Cord velocity curve in the deteriorating group. Graph showing the characteristic pattern in this group: the value of cord velocity (wave I) is small and the velocity change in the caudal direction is also small.

Among the patients with spinal dysraphism, cord velocity was studied in relation to the complications of hydrocephalus and Chiari malformation. Seventeen of the 24 patients with past myelomeningocele surgery had complications of hydrocephalus and had undergone a shunting operation. The ventricular size observed on CT was normal in 5 cases (normal subgroup), slit-like in 6 (slit subgroup), and enlarged in 13 (ventriculomegaly group, Evans' index ≥ 0.3). Cord velocity measured in the sagittal image was 0.45 ± 0.07 cm/s in the normal subgroup, 0.56 ± 0.09 cm/s in the slit subgroup, and 0.47 ± 0.08 cm/s in the ventriculomegaly subgroup. Cord velocity was significantly higher in the slit subgroup than in the ventriculomegaly subgroup (Fig. 6). In terms of Chiari malformation, symptomatic
Chiari malformation was not observed in any of the 24 patients with past myelomeningocele surgery. These patients were divided into two subgroups based on MR images: Chiari subgroup and non-Chiari subgroup. Of the 24 patients, 20 belonged to the former subgroup and the remaining 4 to the latter. Cord velocity measured in the sagittal image was 0.50±0.09 cm/s in the Chiari subgroup, and 0.42±0.08 cm/s in the non-Chiari subgroup. There was no significant difference between the two subgroups, although the value for the Chiari subgroup tended to be slightly larger (Fig. 7).

Cord velocity in wave I was compared among 24 patients with past myelomeningocele surgery, 7 patients with past spinal lipoma surgery, and 3 non-
surgical patients. The results are shown in Fig. 8. The mean cord velocity in wave I in the patients with past myelomeningocele surgery was $0.49 \pm 0.09$ cm/s (0.33 to 0.72) in the sagittal image. The corresponding values in those experiencing spinal lipoma surgery showed a tendency toward lower values: $0.41 \pm 0.16$ cm/s (0.17 to 0.57) in the sagittal image. Though the number of cases was as small as 3, the non-surgical subgroup also showed a tendency toward lower values in these parameters: $0.27$ cm/s (0.11 to 0.50) in the sagittal image.

Cord velocity was also compared among patient subgroups with motor dysfunction levels. The 34 patients were classified according to such levels: 9 without motor dysfunction, 12 with motor dysfunction associated with S2, S1, or lower levels, 7 with motor dysfunction associated with L5 or below, and 6 with motor
dysfunction associated with L4 or above. As shown in Table 3, the mean cord velocity in wave I in the sagittal image was 0.46±0.15 cm/s (0.11 to 0.60) in those without motor dysfunction, 0.40±0.11 cm/s (0.17 to 0.50) in those affected at S2, S1, or lower levels, 0.54±0.12 cm/s (0.38 to 0.72) in those affected at L5 or below, and 0.45±0.13 cm/s (0.20 to 0.53) in those affected at L4 or above. There was no difference in cord velocity in wave I among patient subgroups with motor dysfunction levels. In the transverse image, this parameter did not significantly differ either among these patient subgroups.

Cord velocity was studied in the 4 infants below 1 year of age before and
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Table 3 There is no difference in cord velocity in wave I among patient subgroups with motor dysfunction levels.

<table>
<thead>
<tr>
<th>Motor deficit</th>
<th>Cord velocity (wave I)</th>
<th>Sagittal</th>
<th>Transverse (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(−)</td>
<td></td>
<td>0.46 ± 0.15</td>
<td>0.34 ± 0.15</td>
</tr>
<tr>
<td>(n = 9)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>S2 or S1 &gt;</td>
<td></td>
<td>0.40 ± 0.11</td>
<td>0.34 ± 0.17</td>
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<tr>
<td>(n = 12)</td>
<td></td>
<td></td>
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<tr>
<td>L5 &gt;</td>
<td></td>
<td>0.54 ± 0.12</td>
<td>0.36 ± 0.17</td>
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<tr>
<td>(n = 7)</td>
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<td></td>
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<tr>
<td>L4 ≤</td>
<td></td>
<td>0.45 ± 0.13</td>
<td>0.38 ± 0.11</td>
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<tr>
<td>(n = 6)</td>
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</table>

after the surgery for spinal lipoma. Pre-operative cord velocity in wave I in the sagittal images was 0.23~0.66 cm/s (mean: 0.54), and post-operative cord velocity was 0.62~0.82 cm/s (mean: 0.72). Post-operative cord velocity was increased in 3 of the 4 infants: in the case 1 showing pre-operative cord velocity was 0.22 cm/s and post-operative cord velocity was 0.65 cm/s, in the case 2, 0.66 cm/s (pre-op.), 0.78 cm/s (post-op.) and in the case 3, 0.61 cm/s (pre-op.), 0.82 cm/s (post-op.). In the remaining one case, post-operative cord velocity was unchanged: 0.64 cm/s (pre-op.), 0.62 cm/s (post-op.). There was no significant difference between the pre-operative and post-operative cord velocity.

Discussion

Cord motion is generated by brain motion and CSF pumping related to arterial pulsation. Previously reported measurements were made at the cervical level (25-27), lower thoracic level, and lumbar level (24). In the present study, we strictly limited the site of measurement to the C-3 level. This was because cord motion associated with arterial pulsation would be largest at this level, and because cord velocity curves obtained would more widely vary unless the cervical cord level was precisely specified. Considering possible effects of age on cord motion, we chose relatively young subjects (10 to 39 years). MR images were acquired through a commonly used 2D-cine phase-contrast MRI technique. In the operation of the
Visart system, velocity encoding was set as low as 50 mm/s to cover slow cord motions. After many trials and errors, we obtained quite reproducible and reliable values by defining the region of interest (ROI) with a diameter of one-half to one-third of the cord diameter and by measuring the velocity at the center region of the cord (Fig. 3). In both sagittal and transverse images, 3 regions of interest were defined near the C-3 level, and the reproducibility of velocity measurement was confirmed. Unlike previous studies in which cord motion was measured either in the sagittal image or in the transverse image, we measured it in both sagittal and transverse images if possible. The correlation of measured cord velocity between the sagittal and transverse images was studied in 60 subjects (29 healthy subjects and 31 patients with spinal dysraphism). There was a significant correlation between the two although the values obtained in the transverse image were slightly lower (Fig. 9). In general, measurement in the sagittal images seemed to be more useful because the values varied more widely in the transverse image.

![Graph](image)

**Fig. 9.** The correlation of cord velocity between the sagittal and transverse images. There is a significant correlation between the two (P<0.05). Open circles: patients with spinal dysraphism (n=31), Closed circles: healthy subjects (n=29).

We analyzed not only the values of cord velocity in healthy subjects, but also their cord velocity patterns. Each cord velocity curve was composed of 3 component
waves (waves I, II, and III). According to their time-velocity patterns, cord velocity curves were classified into 3 types. Type I was typical among the healthy subjects. In the curve of this type, cord velocity measured through image acquisitions gated to the R wave first increased in the caudal direction, and then rapidly changed its direction toward the rostral side. After a temporary plateau, the velocity changed its direction again toward the caudal side. Previously, Levy et al. (27) and Mikulis et al. (26) reported on cord motion at the cervical cord level in healthy subjects. Levy et al. seemed to have measured cord velocity only in wave I which we reported here. Their subjects varied in age from 2 to 60 years, and only a limited number of subjects were included in each age group. Mikulis et al. obtained cord velocity curves through R-wave-gated image acquisitions in only 11 subjects. Levy et al. measured cord velocity in waves which seemed to correspond to our wave I, and reported 1.24±0.29 cm/s as the cord velocity at the mid cervical level. Cord velocity measured at the cervical level by Mikulis et al. was 0.7±0.14 cm/s for wave I, and 0.29±0.21 cm/s (in the rostral direction) for wave II. The corresponding values which we obtained were lower than previous reports, but in this report, cord velocity was measured in both sagittal image and transverse image to confirm the reliability and reproduction if possible. Our values were roughly consistent between the sagittal and transverse images: cord velocity in the sagittal image was 0.49±0.11 cm/s for wave I and that in the transverse image was 0.47±0.21 cm/s, respectively.

Comparison was made between the healthy subjects and patients with spinal dysraphism, especially those who had undergone myelomeningocele or spinal lipoma surgery in their neonatal or infant years. TCS is defined as a syndrome characterized by a pathological cord traction resulting in causing neurological dysfunction. The operation performed for myelomeningocele or spinal lipoma in the neonatal or infant years may leave surgical scars, causing tissue adhesions in the corresponding region of the spinal cord. In the present study, the patients with spinal dysraphism were divided into two subgroups: the stable subgroup and deteriorating subgroup. We compared the cord velocity between these two subgroups and healthy subjects (Fig. 4). In the stable subgroup, cord velocity curve patterns were closely similar to those in healthy subjects. Cord velocity of these patients in wave I was 0.50±0.09 cm/s in the sagittal image and 0.38±0.12 cm/s in the transverse image. When compared with the respective values in the healthy subjects (0.49±0.11 cm/s and 0.47±0.21 cm/s), the sagittal value were not different between the two subject groups although the transverse value was slightly lower in the patient subgroup. Thus, in the stable subgroup, post-operative tissue adhesions, if any, did not seem to be so serious as to restrict cord motion at the C-3 level. In the deteriorating
subgroup, on the other hand, cord velocity in wave I was $0.28 \pm 0.13$ cm/s in the sagittal images and $0.22 \pm 0.17$ cm/s in the transverse images. These values were significantly lower than those in the healthy subjects. Also, changes in velocity in wave I were characteristically small in cord velocity curves of this patient subgroup. These results suggest the possibility of TCS due to tissue adhesions in the deteriorating subgroup. A decrease in cord velocity in patients with TCS has been described by Levy et al. and McCullough et al. (25, 27). But, no previous reports analyzed cord velocity changes in wave I from the qualitative point of view. In order to diagnose TCS at an early stage, it seems important to assess wave I qualitatively from cord velocity values as well as quantitatively from the degree of velocity change in wave I.

In patients with past myelomeningocele surgery, associated with Chiari malformation, hydrocephalus, syringomyelia and/or arachnoiditis may affect their cord motion. We studied patients without distinct syrinx or those without diffuse arachnoiditis in the present study. In our patients with past myelomeningocele surgery, CT findings of hydrocephalus were studied in relation to their cord velocity (Fig. 6). The velocity was significantly higher in those having a slit-like ventricle than in those having ventriculomegaly. The latter patients showed cord velocity similar to that of the healthy subjects. In the patients with slit-like ventricle, cord velocity may be increased because the compliance of the brain is lower and brain motion associated with arterial pulsation become larger than in other patients. In terms of Chiari malformation, the patients were divided into two subgroups: Chiari subgroup whose MR images suggested that CSF flow was decreased by the cerebellar tonsil descending into the major cistern, and non-Chiari subgroup whose MR images suggested that CSF flows well in the absence of the descensus of the cerebellar tonsil. Regarding Chiari malformation suspected from MR images, no distinct effect on cord velocity was observed (Fig. 7).

Among the 7 patients showing symptomatic aggravation out of 34 patients in this series, 5 patients with spinal lipoma were not associated with hydrocephalus or Chiari malformation which may affect cord motion. Therefore, a highly suspected cause of their decreased cord velocity was tethering of the cord. In the remaining 2 patients with past myelomeningocele surgery, the tethering of cord was also suspected to greatly contribute to the decreased cord velocity because, as described above, cord velocity did not seem to be affected by ventriculomegaly or Chiari malformation, though both patients showed ventriculomegaly in CT, and one of them also showed Chiari malformation. Thus, it is highly likely that whatever the complications associated with myelomeningocele were, the decrease in cord motion seen in the deteriorating subgroup was thought to be due to the tethering...
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of the cord.

Cord velocity was also studied in relation to clinical symptoms. Six patients with spinal dysraphism showed wave I cord velocity of 0.34 cm/s or lower (Fig. 4), and 5 of them (83%) showed symptomatic aggravation. Thus, in the age group studied, cord velocity of 0.35 to 0.40 cm/s seemed to be a border dividing the patients into the stable and deteriorating subgroups.

Cord velocity was studied in relation to the motor dysfunction level of the spinal cord affected and the type of disease. The spinal level affected was independent of cord motion as shown in Table 3. The mean cord velocity in wave I in the 7 patients with past spinal lipoma surgery was $0.41 \pm 0.16$ cm/s in the sagittal image, and $0.30 \pm 0.14$ cm/s in the transverse image. These values tended to be lower than those in the patients with past myelomeningocele surgery, though there was no significantly difference. The 3 non-surgical patients with spinal lipoma showed a much lower cord velocity ($0.27$ cm/s in the sagittal, and $0.2$ cm/s in the transverse). These facts may support the necessity of preventive surgery for spinal lipoma (28,29). Practically, we assessed cord motion of 4 infants below 1 year of age before and after the surgery for spinal lipoma. Post-operative cord velocity was increased in 3 of the 4 infants and unchanged in the remaining one who was neurologically intact at present, however, must be carefully followed. These results were consistent with the previous report (25). In the infants below 1 year of age, the measurement of cord motion by phase-contrast MRI is possible and is thought to be useful for the evaluation of the tethering before and after the operation of untethering.

From these results, the measurement of cord velocity through phase-contrast MRI techniques is thought to provide a method for objectively and quantitatively assessing cord motion and is considered to be very helpful for early diagnosis and early treatment of TCS. This technique should make non-invasive serial examinations possible, and seems to enable us to predict whether or not untethering surgery will be applicable and effective for the patient. Further study will be needed on healthy subjects to determine the effect of the subject's age or the region of interest on the cord velocity curve as well as the velocity change in wave I.

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