The fate of the compressed deformed spinal cord after decompressive surgery: MR imaging and histopathological findings in experimental studies

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The authors conducted a study in which they applied the spinal cord compression-decompression model in rabbits to investigate the morphological changes and histopathological findings in the deformed spinal cord over a long-term period after performing decompressive surgery.

Throughout the experimental period, magnetic resonance (MR) images were obtained frequently; after obtaining a final MR image, the spinal cord was dissected and underwent histological examination.

Immediately after decompressive surgery, axial T₁-weighted MR imaging revealed an increase in the cross-sectional area of the spinal cord during the 1st and 2nd weeks. The spinal cord area achieved a peak at an average of 5.9 weeks after decompressive surgery, when it displayed isointensity on T₁- and high-intensity on T₂-weighted images. The main histological findings were spongy changes in the white matter, which persisted for 4 months postsurgery. There was a significant correlation between the presurgical spinal cord area and the postsurgical decreased number of motor neuron cells.

Based on the MR imaging and histopathological studies, although the deformed spinal cord that underwent compression for 3 months was immediately restored morphologically after decompressive surgery, the change in quality in the spinal cord persisted at least 4 months.

Key Words * apoptosis * experimental study * decompressive surgery * histopathology * magnetic resonance imaging * spinal cord compression

Many models developed to produce experimental spinal cord compression for histopathological studies have been reported.[1,6,8-10,13,17, 21,38,40,44] There have also been many clinical reports on the relief from clinical symptoms obtained after decompressive surgery for compression myelopathy.[3,11,15,29] Since the advent of magnetic resonance (MR) imaging, a few reports have demonstrated correlation of clinical results and morphological restoration of the compressed deformed spinal cord on MR image findings after decompressive.[15,22,29,30] However, the detailed histopathological conditions of the
spinal cord structure postsurgery for a compressed deformed spinal cord and the correlation between the imaging and the histopathological findings have not yet been reported. In a few reports authors have described the short-term morphological changes in the deformed spinal cord after decompressive surgery.[16] In this study, we have applied the spinal cord compression model in white rabbits to investigate the morphological and histopathological changes in the deformed spinal cord over a longterm period after decompressive surgery. The changes were followed using MR imaging and histopathological evaluations.

**MATERIALS AND METHODS**

**Compression Model**

Twenty-three Japanese white rabbits, with a mean weight of 2.9 ± 0.18 kg (range 2.5-3.1 kg), underwent examination. Experiments were performed after induction of intramuscular anesthesia (30 mg/kg body weight of ketamine and 30 mg/kg body weight of pentobarbital). Each animal was placed in the prone position on the table and was breathing spontaneously during surgery. A single-level laminectomy was then performed in the lumbar spine, and the ligamentum flavum was removed using microscopic guidance. A No. 8 French silicone tube (22.4 mm²), inserted in the ascending direction up into the epidural space, was advanced very slowly to provide a space-occupying lesion. The length of the spinal cord compression that was created by the inserted silicon tube was approximately 5 cm and consisted of two vertebral bodies. The other end of the tube was left in the paravertebral muscle. Compression was maintained for 12 to 15 weeks (mean 13.4 ± 1.0 weeks).

**Decompression Model**

After maintaining compression in the rabbits' spinal cords for an average of 13.4 weeks, each animal was prepared for decompressive surgery in the same fashion as for compressive surgery. The old dorsal wound was reopened, and the tip of the silicon tube was exposed in the paravertebral muscle. The silicone tube was pulled out 2.5 cm (one vertebral-body level), by using real-time fluoroscopic guidance. The distal region in which the tube remained was used as index of the compression area by which to provide an internal marker for the correlation of MR images and histological sections. Morphological changes were investigated at their decompressed level in the spinal cord.

**Assessment of Motor Function**

During these studies, the condition of the motor function of the bilateral hind limbs in the animals was evaluated daily and categorized into one of the six modified Tarlov scale grades.[14,41] (Table 1).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no movement</td>
</tr>
<tr>
<td>1</td>
<td>barely perceptible movement in hind limbs; no weight bearing</td>
</tr>
<tr>
<td>2</td>
<td>frequent &amp; vigorous movement in hind limbs; no weight bearing</td>
</tr>
<tr>
<td>3</td>
<td>can support weight w/ hind limbs; may take 1 or 2 steps</td>
</tr>
<tr>
<td>4</td>
<td>walks w/only mild deficit</td>
</tr>
<tr>
<td>5</td>
<td>normal, but slow walking</td>
</tr>
<tr>
<td>6</td>
<td>full &amp; fast walking</td>
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MR Imaging Investigation

MR images were obtained using a 0.5 Tesla machine (MRT50A/II 0.5T System; Toshiba Electric, Tokyo, Japan). The internal diameter of the circle target coil was 200 mm. The MR imaging was performed using the following conditions: thickness, 5 mm; matrix, 256 X 256. Using the spin-echo sequence, T₁-weighted sagittal and axial images (TR = 500 msec; TE = 20 msec) and T₂-weighted sagittal and axial images (TR = 2000 msec; TE = 80 msec) were obtained in all animals. Magnetic resonance imaging was performed twice: once at 1 week after and then again at 3 months after compression was surgically created. After decompressive surgery, MR imaging was also performed each week for 6 weeks and then every 4 weeks for the following 4 months, providing a follow-up series of nine MR images for examination.

Morphological Changes in the Spinal Cord

To assess the morphological changes in the spinal cord, T₁-weighted axial images were processed to measure the cross-sectional area in the spinal cord by using a Ushikata-type digitizer. Three of the four authors repeated the measurement of the area blindly at least five times, and we used the mean measurement value as the final one. The spinal cord deformities were divided into two groups according to the first MR imaging findings: nine animals in the dorsal and 14 in the lateral compression group. To evaluate the spinal cord deformities, the anteroposterior (AP) diameter and the width of the spinal cord were measured on axial view T₁-weighted MR images. Then, in the dorsal compression group, the AP diameter was divided by the width, and in the with lateral compression group, the width was divided by AP diameter to obtain the compression ratio (Fig. 1).
Fig. 1. Illustrations demonstrating measurement of the compression ratio. To evaluate the spinal cord deformities, the AP diameter and the width (W) of the spinal cord were measured on axial view T1-weighted MR images. In the dorsal compression group (left), the AP was divided by W, whereas in the lateral compression group (right), W was divided by AP, to obtain the compression ratio.

**Histopathological Study**

The experimental period continued for approximately 4 months after decompressive surgery during which MR imaging examinations were performed serially; each animal was then killed by administering an overdose of intravenous ketamine and pentobarbital. The perfusion fixation for microscopic examination was performed according to the following procedure. The thorax was opened, and a cannula
was placed into the left ventricle. Immediately before perfusion, the vena cava inferior was cut, and the vascular system was rinsed through with 1000 ml of phosphate-buffered saline. This was followed by 200 ml of Bouin's fixative. After satisfactory perfusion fixation, the spinal cord (including the experimental segment) was immediately removed from the spine. The spinal cord segment was stored in Bouin's fixative for a few days and then embedded in a paraffin block. Transverse sections 4-µm thick were mounted on glass slides, and staining procedures were performed by using hematoxylin and eosin and Nissl's and Luxol fast blue stains to evaluate histological changes by using light microscopy. To count the anterior horn cells, we followed the method of Kitamura and Sakai[23] and Yamamoto[45] for identifying and classifying anterior horn cells in the spinal cord. The anterior horn cells were divided into three major zones: medial, anterolateral, or dorsoletaral nuclei. The number of motor neurons was counted in these same areas in the spinal cord. All neurons that possessed clearly delineated, centrally located nuclei and abundant Nissl bodies within the perikarya were counted. Neurons that demonstrated a central chromatolysis and a short diameter of less than 2.5µm were excluded from the cell count. The apoptotic cells were stained by in situ end-labelling method in which an Apop Tag Plus (Oncor, Gaithersburg, MD) was used. To perform electron microscopic examinations, the spinal cord was processed into epok 812 blocks and sectioned after satisfactory perfusion fixation followed by 4% phosphate-buffered paraformaldehyde.

RESULTS

Motor Function

The 23 rabbits were classified into one of four groups according to their degree of motor dysfunction based on Tarlov's classification after spinal cord compression was surgically created. There were five cases of Tarlov Grade 1, one Grade 3, three Grade 4, and 14 cases of Grade 5 or 6. From the 3 day to the 7th day after silicon tube insertion, the conditions of the motor function became stable. After that, the conditions were unchanged during the observation period after partial removal of the silicone tube, due to the continued spinal cord compression created by the partially remaining silicon tube. Severe motor dysfunction at Tarlov Grades 1 to 4 was seen in four of the 14 animals (29%) in the lateral compression group and in four of the nine animals (44%) in the dorsal compression group, with no significant difference between the two groups (p = 0.4354). In the lateral compression group, hemiparesis (motor dysfunction in the compression side) was seen in six of the 14 animals (43%), paraparesis in two (14%), and no motor dysfunction was demonstrated in six (43%) animals. In the dorsal compression group, paraparesis was seen eight of the nine cases (89%), and no motor dysfunction was demonstrated in one (11%). There was no occurance of hemiparesis in the dorsal compression group (Table 2).
In all animals, the mean area of the compressed spinal cord was 12.7 ± 3.2 mm² (range 7.6-21.3 mm²) before decompressive surgery was performed. The mean area was 11.2 ± 2.3 mm² (range 8.6-14.7 mm²) in the dorsal compression group, and was 13.6 ± 3.5 mm² (range 7.6-21.3 mm²) in the lateral compression group; there was no significant difference between the two groups (p = 0.0928).

Immediately after decompressive surgery, MR imaging demonstrated that the area of the spinal cord was increased during the 1st and 2nd weeks in all animals of both groups. The area continued to increase into at least the 3rd week, and thereafter there was only a slight tendency to increase in area until the end of the 6th week. The spinal cord area reached a peak at an average of 5.9 weeks after decompressive surgery. The area of the spinal cord achieved a mean peak value of 19.3 ± 3.9 mm² (range from 14.0-26.9 mm²; Fig. 2).

**Morphological Change in the Spinal Cord on MR Imaging**

In all animals, the mean area of the compressed spinal cord was 12.7 ± 3.2 mm² (range 7.6-21.3 mm²) before decompressive surgery was performed. The mean area was 11.2 ± 2.3 mm² (range 8.6-14.7 mm²) in the dorsal compression group, and was 13.6 ± 3.5 mm² (range 7.6-21.3 mm²) in the lateral compression group; there was no significant difference between the two groups (p = 0.0928).

Immediately after decompressive surgery, MR imaging demonstrated that the area of the spinal cord was increased during the 1st and 2nd weeks in all animals of both groups. The area continued to increase into at least the 3rd week, and thereafter there was only a slight tendency to increase in area until the end of the 6th week. The spinal cord area reached a peak at an average of 5.9 weeks after decompressive surgery. The area of the spinal cord achieved a mean peak value of 19.3 ± 3.9 mm² (range from 14.0-26.9 mm²; Fig. 2).
Fig. 2. Graph showing change in the spinal cord area of the compression site. In all cases, the mean area of the compressed spinal cord was $12.7 \pm 3.2 \text{ mm}^2$ (range $7.6 - 21.3 \text{ mm}^2$) before decompressive surgery. Immediately postsurgery, the area of the spinal cord on MR imaging was increased during the 1st and 2nd weeks in all animals of both groups. The area continued to increase into at least the 3rd week, and thereafter there was only a slight tendency to increase in area until the end of the 6th week. The spinal cord area growth reached a peak at an average of 5.9 weeks postsurgery. The area of the spinal cord achieved a mean peak value of $19.3 \pm 3.9 \text{ mm}^2$ (range 14.0-26.9 mm$^2$).

**Spinal Cord Compression Ratio**

In all animals, the spinal cord compression ratio was restored almost to normal within 1 week after decompressive surgery. At an average of $5.4 \pm 4.1$ weeks postsurgery the spinal cord compression ratio achieved its highest value: $4.7 \pm 4.8$ weeks in the dorsal and $5.9 \pm 3.8$ weeks in the lateral compression group; there was no difference between either group (Fig. 3).
Fig. 3. Graphs showing change in the spinal cord compression ratio in the lateral (left) and dorsal (right) compression groups at 1 week after postsurgery until the end of the
experiment. Left: The spinal cord compression ratio was almost restored to normal in all lateral compression group animals within 1 week postsurgery. In this group, the mean compression ratio of the compression site was 99.63 ± 27.28% (range 62.48-153.31%), and the mean compression ratio of the highest value after decompression was 180.41 ± 24.92% (range 133.94-214.81%), with significant difference between the two groups (p < 0.0001). At an average of 5.9 weeks postsurgery, the spinal cord compression ratio achieved its highest value in the lateral compression group animals. Right: The spinal cord compression ratio was almost restored to normal in all dorsal compression group animals within 1 week postsurgery. In this group, the mean compression ratio of the compression site was 27.23 ± 10.11% (range 14.3-50.07%) and the mean compression ratio of the highest value decompressive surgery was 65.85 ± 5.73% (range 53.19-73.01%), with significant difference between the two groups (p < 0.0001). At an average of 4.7 weeks postsurgery, the spinal cord compression ratio achieved its highest value in the dorsal compression group animals.

**Correlation Compression Ratio and Number of Motor Neuron Cells**

There was no significant correlation between the compression ratio and the number of motor neuron cells in either the lateral compression (r = 0.039 p < 0.8959) or dorsal compression group (r = -0.167, p < 0.6803) (Fig.4). In the lateral compression group, when the compression ratio was less than 120%, severe motor dysfunction at Tarlov grades 1 to 4 occurred in four (33%) of 12 animals and in neither of the two animals with a higher than 120% compression ratio. In the dorsal compression group, severe motor dysfunction (Tarlov Grades 1-4) occurred in five (56%) of nine animals when the compression ratio was less than 50%.
Fig. 4. Scatterplots showing the correlation between the spinal cord compression ratio and the number of motor neuron cells. Left: In the lateral compression group, there was no significant correlation between compression ratio and number of motor neuron cells \( (r = 0.039, p < 0.8959) \). Severe motor dysfunction at Tarlov Grades 1 to 4 (black scatterplots) occurred in four (33%) of 12 animals when the compression ratio was less than 120% and in four animals (33%) when the number of motor neuron cells was less than 100. Right: In the dorsal compression group, there was no significant correlation between compression ratio and number of the motor neuron cells \( (r = -0.167, p < 0.6803) \). Severe motor dysfunction at Tarlov Grades 1 to 4 (black scatterplots) occurred in five (56%) of nine animals when the compression ratio was less than 50%, and in five animals (63%) when the number of motor neuron cells was less than 70.

**Correlation of Spinal Cord Area and Number of Motor Neuron Cells**

There was a significant correlation between the spinal cord area and the number of motor neuron cells in both the lateral compression group \( (r = 0.727, p < 0.0022) \) and the dorsal compression group \( (r = 0.463, p < 0.2197) \) (Fig. 5). In the 14 animals in the lateral compression group, the motor function was maintained (Tarlov Grades 5 or 6) in 10 cases in which the area was more than 15 mm\(^2\) or the number of...
motor neuron cells was maintained at more than 50. Severe motor dysfunction (Tarlov Grades 1-4) occurred in four of the 10 animals in which the spinal cord area was less than 15 mm² (Fig. 5 upper). In the dorsal compression group, whereas the area in each of all the nine rabbits was less than 15 mm², the severe motor dysfunction was seen in five rabbits. The number of motor neuron cells in these five rabbits with severe motor dysfunction ranged from 10 to 62 (mean 41 ± 20), whereas that in the other 4 animals with slight motor dysfunction ranged from 28 to 73 (mean 54 ± 20) (Fig. 5 lower ); with no significant difference between them (p = 0.3272).
Fig. 5. Scatterplots showing the correlation between the spinal cord area and the number of motor neuron cells. Upper: In the lateral compression group, there was a significant correlation between the decreased spinal cord area and the decrease in the number of motor neuron cells \( (r = 0.727, \ p < 0.0022) \). Severe motor dysfunction occurred in four (40%) of 10 animals when the spinal cord area was less than 15 mm\(^2\), and in four (33%) of 12 cases when the number of motor neuron cells was less than 100. Lower: In the dorsal compression group, there was a significant correlation between the decreased spinal cord area and the decrease in the number of motor neuron cells \( (r = 0.463, \ p < 0.2197) \). Severe motor dysfunction occurred in five (56%) of nine animals when the spinal cord area was less than 15 mm\(^2\), and in five (63%) of 8 animals when the number of motor neuron cells was less than 70.

**Histopathological findings**

After decompressive surgery in the region in which decompression was performed, the shape of the spinal cord was restored almost to normal on both the white matter and the gray matter. Analysis of the histological findings indicated marked edema (tissue loosening) of the white matter, particularly near the vessel in gray matter at the compression site. The spinal cord swelling of the region in which decompressive surgery was performed in the lateral compression group was more severe in the compression region than the contralateral region. In all cases, examination of the hematoxylin and eosin-stained sections demonstrated that there were many microcysts not only in the compression region but also on the other side of the white matter, which indicated that edematous change occurred in the white matter. Motor neuron cell loss was demonstrated in the anterior horn of their gray matter in 20 of 23 animals. The loss of neuron cells was asymmetrical in the lateral compression group. Cell loss was also seen contralaterally but to a lesser degree. Evidence of necrosis involving the gray matter was seen in 10 cases. In three animals frank macrocavitation of the spinal cord, located mainly in the gray matter, occurred at the level of compression. In three animals there was an increase in the acidophilicity, and in one case there was infiltration of lymphocytes from a vessel and widening in the central canal. In the spinal cord region subjected to continuous compression after a period of 7 months, compression deformity both in white and gray matter was found, the neuron cells in the anterior horn of the compression region decreased, and there was deformity. In the continuously compressed region, the white matter became a dented deformation, and on the other side, gray matter became stretched and
deformed vertically at right angles from the direction of pressure. The edematous change was more severe in the compressed side.

Following decompressive procedures in all animals, there were apoptotic cells that were stained using positive terminal deoxynucleotidyl transferase-mediated dUTP-biotin nick-end labeling (TUNEL) both in the gray matter and the white matter, involving not only the compressed region but also the contralateral side. Many apoptotic cells were found in the region in which severe edematous changes occurred with vascularization (Fig. 6). The apoptosis was confirmed using electron microscopy; the nucleus was strongly stained like a necklace (Fig. 7).

Fig. 6. Photomicrograph showing apoptotic cells in both the white and the gray matter. Many apoptotic cells were found in regions with vascularization with severe edematous changes. Terminal deoxynucleotidyl transferase-mediated dUTP-biotin nick-end labeling (TUNEL) stain, X 45.

Fig. 7. Electron micrograph showing nucleus strongly stained like a necklace. Bar = 1µm.

Correlation of MR Imaging and Histopathological Findings
The change in the signal intensity in the spinal cord was investigated by examining findings from T₁ and T₂ weighted sagittal and axial MR images. When the region of the spinal cord was shown as isointensity on T₁ images and as high intensity on T₂ images after decompressive surgery, the histological findings demonstrated by hematoxylin and eosin stain showed that many microcysts were not only in the compression region but also in other white matter, indicating the occurrence of edematous change in the white matter. These MR imaging findings developed throughout the follow-up period. Use of the histological examinations confirmed loss in motor neuron cells, with no specifically correlated findings on the MR imaging. When the region of the spinal cord was shown as T₁-weighted low signal intensity and as T₂-weighted high intensity signal, the analysis of the histological findings demonstrated more severe edematous change in the white matter. Moreover, when the spinal cord was shown as T₁ and as T₂-weighted high signal intensity, there was severe motor dysfunction, and analysis of the histological findings showed severe deformity at the dorsal horn with severe motor neuron cell loss. The change in signal intensity was seen until 6 weeks postsurgery; thereafter, the change was not seen throughout the follow-up period. Almost all animals showed no change in signal intensity in the follow-up period. In some spinal cords, a transient T₁-weighted low-intensity signal was revealed at 1 week postsurgery. Moreover, when a T₁ high-intensity signal was demonstrated at the compression site, the signal intensity was unchanged after the decompressive procedure; in such cases there was severe motor dysfunction. When the MR imaging findings were examined for evidence of motor paresis in the mild motor dysfunction group (Tarlov Grades 5 or 6), 11 (79%) of the 14 animals demonstrated T₁ isointensity and T₂-weighted high-intensity signals. In contrast, in the severe motor dysfunction group (Tarlov Grades 1-4, five of the 10 animals (50%) demonstrated T₁ high-intensity signals or low high-intensity and T₂-weighted high-intensity signals (Table 2).

DISCUSSION

In studies of the experimental chronic compression model, there have been various methods used including gradual compression screws,[36,39] balloons,[26] tumors,[19] cytokines (BMP),[28,35,37] and other devices.[4,5,12,18,20,27,31,32,42,43] It has remained difficult to maintain a constant compression state by using liquid or gas because of the animal’s movement. Prior to beginning this study, we attempted to use several methods to compress the spinal cord. Several materials of various sizes were examined and selected for stable experimental conditions. From these trials, we have developed a stable spinal cord compression-decompression model by using a simple technique in which a silicone tube was inserted into the epidural space to produce constant compression that was reliably reproducible, and we have used this model to study morphological changes in the deformed spinal cord of animals after decompressive surgery over a long-term period. Because we developed a low invasive model and because the silicone tube was suitable and safe for long-term in vivo use, we were able to obtain many follow-up serial MR images.

There have been reports of spinal cord compression related to nerve function. In an acute compression model, Yasukawa[46] and Takahashi, et al.,[40] have reported that the percentage of amplitude (initial spike potentials) decreased as the severity of the injury causing compression increased. In a chronic compression model, Sakou, et al.,[36] have reported that motor paralysis occurred when the compression ratio was above 70%. Sato, et al.,[37] have reported that delays in latency were found in the evoked spinal cord potentials from each stimulation site when the compression ratio was above 10%. Baba, et
al.,[2] reported, based on an experiment in which tip-toe-walking Yoshimura mice were studied, that there was a significant correlation between the compression ratio and the number of motor neuron cells. In only a few reports have there been descriptions of the morphological changes in the deformed spinal cord after decompressive surgery over a long-term period. Harkey, et al.,[16] have previously described the MR images and the spinal cord blood flow after decompressive surgery in an experimental chronic compression model. Reporting on an applied mean 29% canal stenosis model in which canines were used, these authors reported that, after 4 months of compression, decompressive surgery improved dramatically the neurological findings; however, analysis of the histopathological findings demonstrated that there had been irreversible change in four of six dogs. In the present study, severe motor dysfunction occurred in five of the nine animals in which the compression ratio was less than 50%, which is a known characteristic in the acute spinal cord compression model. Motor function was maintained in those animals in which the area was more than 15 mm² (78% of the mean of finally recovered area) or the number of motor neuron cells was maintained at more than 50 (43% of normal ratio).

When is the restoration of a deformed spinal cord completed by decompressive surgery? From early T1-weighted MR images obtained after decompressive surgery in patients with cervical myelopathy, the cord deformity was at least partially restored immediately postoperatively.[30] In the present compression-decompression model, the form of the spinal cord after maintaining compression for 3 months was restored to the original state within 1 week. This demonstrated well the plasticity of the spinal cord, and the finding was consistent with our previous clinical reports in which we investigated the MR imaging findings in patients with cervical myelopathy.[30] Animals in which penetration of the dura occurred during tube insertion developed severe spinal cord injury and were consequently excluded from the experimental study. In these cases, their spinal cord demonstrated poor morphological recovery after partial removal of the tube, and severe deformity persisted (Fig. 8).

Fig. 8. Photomicrograph showing the deformed spinal cord (transverse section). Animals in which penetration into the dura occurred during tube insertion developed severe spinal cord injury showed poor recovery morphologically after partial removal of the tube, and severe deformity persisted. Analysis of these findings suggested that to maintain spinal cord plasticity, it was important to cause no damage to the outer membrane of the spinal cord (such as the pia matter and arachnoid membrane) and also to preserve flow of the cerebrospinal fluid and its pressure. H & E, X 14.

Analysis of these findings suggested that, to cause spinal cord plasticity, it was important to maintain no damage to the outer membrane of the spinal cord (such as the pia matter and arachnoid membrane) and also to maintain flow of the cerebrospinal fluid and its pressure. Even if MR imaging demonstrated that
the spinal cord form was restored to its original size, there was motor neuron cell loss in the gray matter and spongy changes occurred in the white matter. Izumida[19] has reported a chronic spinal cord compression model with a 354A tumor, in which the mild compression group demonstrated spongy change at the site of compression and demyelination in the white matter, the moderate compression group demonstrated gliosis and severe demyelination, and the severe compression group demonstrated spinal cord atrophy of the entire compression site with simple atrophy, loss of anterior horn cells, and a hemorrhagic lesion in the intramedullary region. In the present study, although the compressed, deformed spinal cord was restored and maintained for 4 months after decompressive surgery, the histological findings were similar to those obtained by Izumida. When we investigated a possible correlation between the compression ratio and the number of motor neuron cells, and any correlation between the spinal cord area and the number of motor neuron cells, we found no correlation between the compression ratio and the number of motor neuron cells; however, a correlation was revealed between the spinal cord area and the number of motor neuron cells. This was because although the spinal cord had a compression deformity, when the spinal cord was extended vertically at right angles from the direction of pressure, then the spinal cord area itself would be unaffected. It was therefore postulated that the enough space for the motor neuron cells was maintained. On the other hand, the number of motor neuron cells and their function were also controlled normally by the apoptotic mechanism.[7,25,33,34] It was remarkable and interesting therefore that apoptotic cells were found not only in the compressed region but also on the side contralateral to the compression. In particular, many apoptotic cells were found in the region where severe edematous changes occurred. This indicated that neuron cells avoided from necrotic cell death, and went on to apoptotic cell death by secondary edematous damage. Regarding the motor paralysis, however, we have repostulated that the degree of motor paralysis was controlled by the spinal cord area rather than by the spinal cord compression ratio.

Based on analysis of clinical reports, the morphological restoration of the deformed spinal cord after decompressive surgery was significantly correlated with clinical results according to the morphological spinal cord findings on the T1 weighted MR image.[30] However, in these clinical cases, patients with complete MR imaging-documented restoration of the deformed spinal cord do not always fully recover from their clinical symptoms. When the patients with myelopathy demonstrated a high signal intensity in their spinal cord on T2-weighted MR image and a low-intensity signal on T1-weighted images after decompressive surgery, some of them continued to demonstrate neurological deficits.[24] In our present study, there was no significant axial MR imaging finding that correlated with the loss in neuron cells. However, the MR images did reveal mild spongy change in the white matter, visualized on T1-weighted images as isointense and on T2-weighted images as high intensity signals. Moderate spongy change was visualized on T1- as low intensity and on T2-weighted images as highintensity signals. Moreover, both T1- and T2-weighted high-intensity images were obtained from cases of severe paralysis and indicated severe deformity in the dorsal horn with severe neuron loss. Therefore, an abnormal intensity demonstrated on MR imaging in the spinal cord was correlated with histologically severe damage in the spinal cord. These MR and histopathological findings were consistent with known clinical evidence.

CONCLUSIONS

The morphological changes demonstrated in the deformed spinal cord after decompressive surgery occurred immediately postoperatively. Even if the spinal cord form was shown to be restored to the original size on MR imaging, there were motor neuron cell loss in the gray matter and spongy changes in the white matter. There was a significant correlation between the presurgery spinal cord area and the...
postsurgery decreased number of motor neuron cells. Many apoptotic cells were found in the region where severe edematous changes occurred. Analysis of these findings suggested that the total spinal cord function after decompressive surgery for a compressed spinal cord was determined by the number of alive neurons controlled from the presurgery spinal cord area and the secondary edematous damage.

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References


45. Yamamoto S: [A histometric quantitative analysis of the neurons and the arteries in the spinal cords with aging.] *J Kurume Med Assoc* **51**:701-109, 1988 (Jpn)

46. Yasukawa K: [Experimental and clinical studies of the evoked electrospinogram for monitoring spinal cord function.] *J Jpn Orthop Assoc* **54**:1661-1677, 1980 (Jpn)