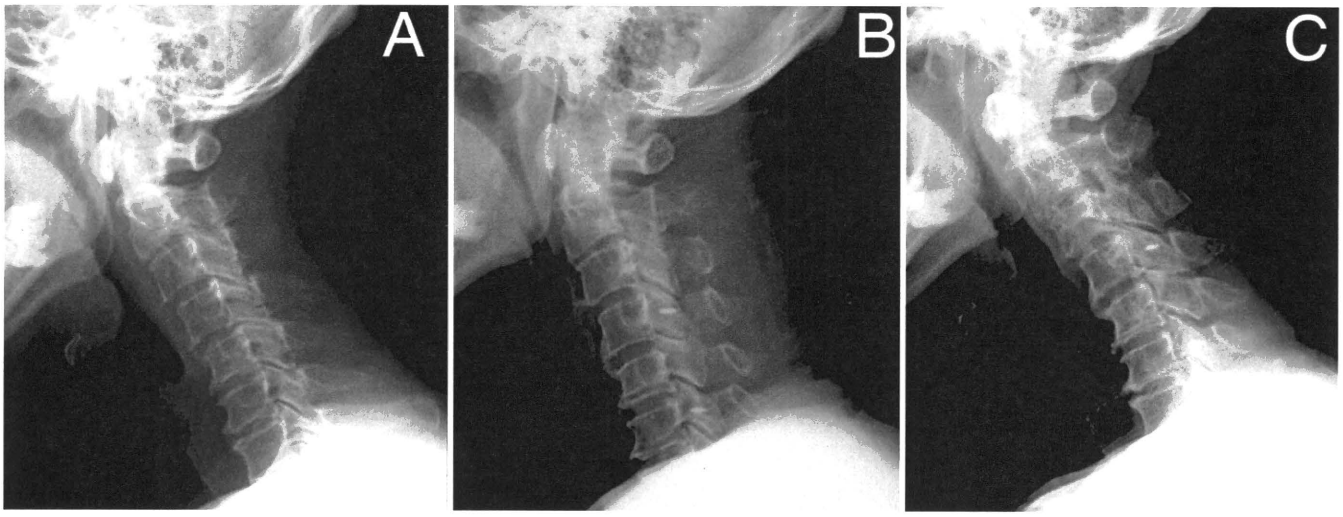

FIG. 6. Lateral radiographs obtained in a 70-year-old man with preoperative kyphosis in whom lamina closure developed despite the use of anchor screws. This patient had cervical spondylotic myelopathy with mild cervical kyphosis before surgery. The CBR of 0.81 before surgery (A) increased to 1.35 immediately after surgery (B), and decreased to 1.10 at the final follow-up examination (C). The patient obtained moderate neurological recovery (recovery rate of 48%), but was slightly dissatisfied with his surgery.

too low. However, we believe this cutoff value to be reasonable because there was no significant difference in the agreement rates of the quantitative and qualitative evaluation under the different cutoff values of 10 and 15%; 79% of patients fell within the cutoff value of 10%, and 82% were within the cutoff of 15%. Another reason for the discrepancy is that patients with a reduction in the CBR at only 1 level are also included in the lamina closure group. Nonetheless, we believe that these criteria are clinically relevant, especially now as spine surgeons try to limit the number of lamina expanded to prevent the development of postoperative axial pain.[9,24]

In the present study, lamina closure detected using the quantitative method was observed in 34% of patients. Lamina closure was observed 3 months after surgery, perhaps because the opened lamina remains unstable in the early postoperative phase. Bone formation occurs on the hinge side in the late postoperative phase, however, making the hinge stronger enough to prevent the laminae from further closure.[6,7]

Lamina closure was not related significantly to improvement in JOA scores, which tended to be better in the lamina closure group, and no patient underwent a revision surgery for neurological deterioration attributable to lamina closure. Therefore, lamina closure may not be problematic in terms of neurological recovery at least for a short postoperative period. However, patients with lamina closure tended to be less satisfied with surgery. The reason for this finding was not clear because we did not evaluate the specific reasons for the patients' satisfaction or dissatisfaction. We speculate that patients may be concerned about possible neurological deterioration in the future due to lamina closure. The inconsistency of several outcome measurements including JOA scores and patients' satisfaction may be due to the multiple factors influencing surgical outcomes, including not only lamina closure, but also presence of kyphosis, cause of myelopathy (cervical spondylosis or OPLL), patient age, and preoperative expectations for surgery.

The only risk factor for lamina closure that we identified was the presence of postoperative kyphosis. Biomechanically, the cervical spine in kyphosis is considered to have greater flexural stresses than that in lordosis.[4] In this situation, the opened laminae may be subject to more compression force by the posterior musculature, and the laminar door may be pushed forward and closed again. Although the presence of kyphosis has been known to be a factor related to unfavorable surgical outcomes after laminoplasty, and the majority of spine surgeons favor anterior surgery in patients with cervical kyphosis, several authors do not consider the presence of preoperative kyphosis in itself an absolute contraindication for laminoplasty. Chiba and colleagues[3] reported that patients with myelopathy due to cervical spondylosis were more likely than patients with OPLL to obtain a favorable neurological recovery, even with kyphosis. These authors attributed this to the redundancy of the spinal cord induced by multilevel spondylosis. Suda et al.[23] reported that patients with preoperative kyphosis < 13° can obtain moderate neurological recovery, but they found that patients with local kyphosis > 13° had poor surgical outcomes, and they recommended anterior decompression surgery or posterior correction of kyphosis for those patients. We have also indicated open-door laminoplasty to patients with mild to moderate cervical kyphosis measuring < 20°.

According to our finding that kyphosis is a risk factor for lamina closure, there is a need to use some preventative measures in addition to Hirabayashi's original method in a subset of patients with kyphosis. Because patients with kyphosis are likely to obtain less of a decompressive effect after laminoplasty compared to those without,[14] they may be more affected by lamina closure,

possibly resulting in suboptimal neurological recovery or later neurological deterioration. This is especially true of patients with OPLLs, which have a tendency to enlarge despite decompression surgery.[8,18,26] A possible solution for lamina closure is to slow the postoperative rehabilitation process. Wearing a cervical brace may be another solution. Other authors have noted however that these methods can have an adverse effect on the development of postoperative axial pain.[11] The anchor screws we used proved ineffective despite the findings of some other authors who reported their efficacy in keeping lamina opened. We therefore suggest that additional procedures such as placement of lamina spacers and plates to prevent lamina closure may be necessary in patients with cervical kyphosis. Laminoplasty may need to be avoided altogether if the kyphosis is severe (> 13° kyphotic angle).

The limitations of the present study include its retrospective nature and relatively short follow-up period. We must conduct follow-up in a cohort for a longer period of time to clarify what degree of lamina closure results in later neurological deterioration. Because our intent was to find risk factors for lamina closure, all patients followed the same postoperative clinical path. Because differences in the postoperative protocol could be a confounding factor for lamina closure, we included only patients who underwent treatment with a recently established postoperative protocol that encourages patients to stand, walk without brace, and start neck exercises as early as possible postoperatively to prevent the development of axial symptoms.

Regardless of its limitations, the present study is the first to clarify the prevalence, clinical consequences, and risk factors of lamina closure using the objective quantitative method, and provides baseline data for future long-term investigations of the relationship between clinical outcome and lamina closure.

Conclusions

Lamina closure was significantly associated with preoperative cervical kyphosis and tended to result in unfavorable patient satisfaction, although it was not significantly related to neurological recovery during the follow-up period of the study. Anchor screws were not effective in the prevention of lamina closure. In patients with preoperative cervical kyphosis, additional procedures to prevent lamina closure may be necessary, such as the placement of spacers and plates, or laminoplasty should be avoided if the kyphosis is severe.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

References

1. Chiba K, Ogawa Y, Ishii K, Takaishi H, Nakamura M, Maruiwa H, et al: Long-term results of expansive open-door laminoplasty for cervical myelopathy—average 14-year follow-up study. **Spine 31:**2998–3005, 2006
2. Chiba K, Toyama Y, Matsumoto M, Maruiwa H, Watanabe M, Hirabayashi K: Segmental motor paralysis after expansive open-door laminoplasty. **Spine 27:**2108–2115, 2002
3. Chiba K, Toyama Y, Watanabe M, Maruiwa H, Matsumoto M, Hirabayashi K: Impact of longitudinal distance of the cervical spine on the results of expansive open-door laminoplasty. **Spine 25:**2893–2898, 2000
4. Harrison DE, Harrison DD, Janik TJ, William Jones E, Cailliet R, Normand M: Comparison of axial and flexural stresses in lordosis and three buckled configurations of the cervical spine. **Clin Biomech (Bristol, Avon) 16:**276–284, 2001
5. Hirabayashi K, Miyakawa J, Satomi K, Maruyama T, Wakano K: Operative results and postoperative progression of ossification among patients with ossification of cervical posterior longitudinal ligament. **Spine 6:**354–364, 1981
6. Hirabayashi K, Toyama Y, Chiba K: Expansive laminoplasty for myelopathy in ossification of the longitudinal ligament. **Clin Orthop Relat Res 359:**35–48, 1999
7. Hirabayashi K, Watanabe K, Wakano K, Suzuki N, Satomi K, Ishii Y: Expansive open-door laminoplasty for cervical spinal stenotic myelopathy. **Spine 8:**693–699, 1983
8. Hori T, Kawaguchi Y, Kimura T: How does the ossification area of the posterior longitudinal ligament thicken following cervical laminoplasty? **Spine 32:**E551–E556, 2007
9. Hosono N, Sakaura H, Mukai Y, Fujii R, Yoshikawa H: C3-6 laminoplasty takes over C3-7 laminoplasty with significantly lower incidence of axial neck pain. **Eur Spine J 15:**1375–1379, 2006
10. Hosono N, Yonenobu K, Ono K: Neck and shoulder pain after laminoplasty. A noticeable complication. **Spine 21:**1969–1973, 1996
11. Iizuka H, Nakagawa Y, Shimegi A, Tsutsumi S, Toda N, Takagishi K, et al: Clinical results after cervical laminoplasty: differences due to the duration of wearing a cervical collar. **J Spinal Disord Tech 18:**489–491, 2005
12. Itoh T, Tsuji H: Technical improvements and results of laminoplasty for compressive myelopathy in the cervical spine. **Spine 10:**729–736, 1985
13. Japanese Orthopaedic Association: [Scoring system for cervical myelopathy.] **J Jpn Orthop Assoc 68:**490–530, 1994 (Jpn)
14. Kawakami M, Tamaki T, Ando M, Yamada H, Yoshida M: Relationships between sagittal alignment of the cervical spine and morphology of the spinal cord and clinical outcomes in patients with cervical spondylotic myelopathy treated with expansive laminoplasty. **J Spinal Disord Tech 15:**391–397, 2002
15. Lee JY, Hanks SE, Oxner W, Tannoury C, Donaldson WF 3rd, Kang JD: Use of small suture anchors in cervical laminoplasty to maintain canal expansion: a technical note. **J Spinal Disord Tech 20:**33–35, 2007
16. Matsumoto M, Nojiri K, Chiba K, Toyama Y, Fukui Y, Kamata M: Open-door laminoplasty for cervical myelopathy resulting from adjacent-segment disease in patients with previous anterior cervical decompression and fusion. **Spine 31:** 1332–1337, 2006
17. O'Brien MF, Peterson D, Casey AT, Crockard HA: A novel technique for laminoplasty augmentation of spinal canal area using titanium miniplate stabilization. A computerized morphometric analysis. **Spine 21:**474–484, 1996
18. Ogawa Y, Chiba K, Matsumoto M, Nakamura M, Takaishi H, Hirabayashi H, et al: Long-term results after expansive open-door laminoplasty for the segmental-type of ossification of the posterior longitudinal ligament of the cervical spine: a comparison with nonsegmental-type lesions. **J Neurosurg Spine 3:** 198–204, 2005
19. Ogawa Y, Toyama Y, Chiba K, Matsumoto M, Nakamura M, Takaishi H, et al: Long-term results of expansive open-door laminoplasty for ossification of the posterior longitudinal lig-

ament of the cervical spine. **J Neurosurg Spine 1:**168–174, 2004
20. Park AE, Heller JG: Cervical laminoplasty: use of a novel titanium plate to maintain canal expansion—surgical technique. **J Spinal Disord Tech 17:**265–271, 2004
21. Satomi K, Nishu Y, Kohno T, Hirabayashi K: Long-term follow-up studies of open-door expansive laminoplasty for cervical stenotic myelopathy. **Spine 19:**507–510, 1994
22. Satomi K, Ogawa J, Ishii Y, Hirabayashi K: Short-term complications and long-term results of expansive open-door laminoplasty for cervical stenotic myelopathy. **Spine J 1:**26–30, 2001
23. Suda K, Abumi K, Ito M, Shono Y, Kaneda K, Fujiya M: Local kyphosis reduces surgical outcomes of expansive open-door laminoplasty for cervical spondylotic myelopathy. **Spine 28:** 1258–1262, 2003
24. Tsuji T, Asazuma T, Masuoka K, Yasuoka H, Motosuneya T, Sakai T, et al: Retrospective cohort study between selective and standard C3-7 laminoplasty. Minimum 2-year follow-up study. **Eur Spine J 16:**2072–2077, 2007
25. Wang JM, Roh KJ, Kim DJ, Kim DW: A new method of stabilising the elevated laminae in open-door laminoplasty using an anchor system. **J Bone Joint Surg Br 80:**1005–1008, 1998
26. Yamazaki A, Homma T, Uchiyama S, Katsumi Y, Okumura H: Morphologic limitations of posterior decompression by midsagittal splitting method for myelopathy caused by ossification of the posterior longitudinal ligament in the cervical spine. **Spine 24:**32–34, 1999
27. Yang SC, Yu SW, Tu YK, Niu CC, Chen LH, Chen WJ: Open-door laminoplasty with suture anchor fixation for cervical myelopathy in ossification of the posterior longitudinal ligament. **J Spinal Disord Tech 20:**492–498, 2007

Manuscript submitted April 29, 2008.
Accepted August 26, 2008.
A part of this work was presented at the 35th Annual Meeting of Cervical Spine Research Society at San Francisco, California, November 29 to December 1, 2007.
Address correspondence to: Morio Matsumoto, M.D., Department of Orthopaedic Surgery, School of Medicine, Keio University, 35 Shinanomachi, Shinjuku-ku, Tokyo, 160-8582, Japan. email: morio@sc.itc.keio.ac.jp.

ELSEVIER

Clinical Neurophysiology 119 (2008) 1111–1118

www.elsevier.com/locate/clinph

Evaluation of segmental spinal cord evoked magnetic fields after sciatic nerve stimulation

Shoji Tomizawa, Shigenori Kawabata *, Hiromichi Komori, Yuko Hoshino Fukuoka, Kenichi Shinomiya

Department of Frontier Surgical Therapeutics, Section of Orthopedic and Spinal Surgery, Division of Advanced Therapeutical Sciences, Graduate School of Tokyo Medical and Dental University, 1-5-45 Yushima, Bunkyo-ku, Tokyo 113-8519, Japan

Accepted 14 January 2008
Available online 11 March 2008

Abstract

Objective: We have previously reported that the measurement of spinal cord evoked magnetic fields (SCEFs) could be a helpful method for evaluating spinal cord function or detecting conduction blocks in the spinal cord. However, there have been no reports about segmental-SCEFs as a complex of axonal and synaptic activities in the spinal cord. The purpose of this study is to record and evaluate segmental-SCEFs.

Methods: The segmental-SCEFs were measured over the lumbar dural tubes of adult rabbits using our SQUID system following sciatic nerve stimulation; spinal cord evoked potentials (SCEPs) were also measured to compare the results.

Results: SCEPs showed conductive sharp waves following gentle waves, suggesting action potentials and synaptic potentials, respectively. The isomagnetic field maps of SCEFs showed a quadrupolar pattern propagating from the caudal to the cranial region within a short latency time, and after the conductive magnetic fields passed, stationary dipolar fields appeared and were sustained at some vertebral levels.

Conclusions: The quadrupolar magnetic fields were estimated to be generated from conducting action potentials, and the dipolar fields were thought to be caused by synaptic activities.

Significance: Through the measurement of segmental-SCEFs, the conductive neural and synaptic activities in the spinal cord can be visualized and distinguished. This is the first report to record and visualize the sequence of events ranging from the axonal activities of peripheral nerves and the spinal tract to the synaptic activities in the spinal cord.

© 2008 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.

Keywords: Synaptic activity; Spinal cord evoked potential; Spinal cord evoked magnetic field; Neuromagnetic recording; Sciatic nerve; Segmental-SCEF

1. Introduction

Pioneered in 1968, magnetoencephalography (MEG) (Cohen, 1968), which involves detecting magnetic fields produced by synaptic activities in the cortex, is already widely approved both for clinical use and for basic science research.

Compared with measurement of electric potentials, magnetic fields are less influenced by surrounding tissue and neuromagnetic recordings also have a theoretical advantage for spatial resolution (Trahms et al., 1989; Hashimoto et al., 1994; Mackert et al., 1997). We previously reported that spinal cord evoked magnetic fields (SCEFs) after spinal cord stimulation could be detected, and we were able to identify a conduction block at the site of a spinal cord lesion for the first time in an animal study (Kawabata et al., 2002). These signals are estimated to originate from neural conductive action potentials in the white matter of the spinal cord.

When considering spinal cord function, synaptic activities in the gray matter are as important as the neural conductive activities in the white matter. Because conductive neural activities in the white matter and synaptic activities

* Corresponding author. Tel.: +81 3 5803 5279; fax: +81 3 5803 5281.
E-mail address: kawabata.orth@tmd.ac.jp (S. Kawabata).

1388-2457/$34.00 © 2008 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.clinph.2008.01.017

in the gray matter are almost simultaneous and adjacent, it was thought to be difficult to separate the two types of neural activities by neuromagnetic recordings.

Though conductive neural activities from the peripheral nerve to the cauda equina or the synaptic activities of the spinal cord in humans have been previously reported by neuromagnetic recordings (Mackert et al., 1997, 2001a,b; Klein et al., 2006), there was no continuance between the two events. And there have been no detailed reports about a sequence which bridges the axonal activities of peripheral nerves and spinal tract with the synaptic activities in the spinal cord (segmental-SCEFs).

The purpose of this study was to record and evaluate segmental-SCEFs as a complex of axonal and synaptic activities, making a close comparison with the results of spinal cord evoked potential (SCEP) measurements in the same subjects.

2. Materials and methods

2.1. Materials and preparation

Eight rabbits (adult Japanese white, 2.5–3.0 kg) were used for these experiments. Initially, anesthesia was induced with ketamine chloride (25 mg/kg, i.m.) and medetomidine chloride (0.1 mg/kg, s.c.). An intravenous infusion of ketamine chloride (20 mg/kg/h), medetomidine chloride (0.1 mg/kg/h) and vecuronium bromide (0.3 mg/kg/h) was used to maintain a completely relaxed muscle condition. A tracheotomy was performed and ventilation was maintained by a tracheal tube on a respirator. The general conditions of the rabbits were monitored by using an electrocardiogram.

Lumbar laminectomy from L4 to L7 was carefully performed in order to expose the dural tube for measurements of SCEPs. Bilateral sciatic nerves were also exposed for stimulation at the mid-thigh by a posterior approach.

2.2. Positioning for the measurements

The rabbits were placed prone on an X–Y–Z coordinate stage; the lumbar dural tubes were placed on the horizontal X–Y plane directed in parallel with the Y-axis.

2.3. Stimulation

Electrical stimuli (square wave pulses, 0.03 ms in duration, 5–8 mA in intensity) were applied to the sciatic nerve of one side just above its bifurcation using a bipolar electrode, MEB2200 (Nihon Koden, Japan). The frequency of the stimulation was designed using different conditions (10 Hz and 60 Hz) to examine the effect of synaptic fatigue.

2.4. Measurements

2.4.1. SCEP (spinal cord evoked potential)

SCEPs were recorded to compare the result with that of segmental-SCEFs, under the same stimulating conditions, at several points spaced 10 mm apart along the median of the exposed dural tube. SCEPs were measured by bipolar recordings such that a reference electrode was placed at 5 mm cranially on the dural tube (Fig. 1a). Fifty to 100 trials were averaged at each point, and the signals were acquired with 10 Hz to 5 kHz band pass filtering.

2.4.2. SCEF (spinal cord evoked magnetic field)

Magnetic recordings were taken with an 8-channel SQUID (Superconducting Quantum Interference Devices) system (Kanazawa Institute of Technology, Japan) in a magnetically shielded room (Adachi et al., 2006). Each channel was arranged in a 2×4 parallel configuration (with a 21 mm distance between neighboring channel positions). The baseline between the pick-up coils and the reference coils was 50 mm, and each pick-up coil was 15 mm in diameter (Fig. 1b).

For all magnetic recordings, the dewar bottom was placed on a plane about 5 mm over the lumbar dural tube. A rectangular measurement grid was obtained by moving the dewar sequentially on the same plane. Each measurement point was spaced 10.5 mm apart along the X-axis and 7 mm apart along the Y-axis, and all SCEFs were measured at about 96 different points (Fig. 1c). Approximately 3000 trials were averaged at each position, and the signals were acquired at a sampling rate of 40 kHz, with 10 Hz to 5 kHz analog band pass filtering.

2.5. Estimation of current sources

The minimum-norm estimation as a spatial filtering method, a popular method for estimating the current distribution in the human brain from magnetic field measurement (MEG) without detailed information about the generator profile, was adopted to estimate the current sources from the obtained data in technical cooperation with Tokyo Metropolitan University (Iwaki and Ueno, 1998; Sekihara et al., 2001, 2005, 2006; Matsuura and Okabe, 1995). Estimated current sources were visualized and referred to the X-ray image to match the localization of the spine and the spinal cord.

After the study, the animals were euthanized by intravenous infusion of pentobarbital (120 mg/kg). The study method was approved by the Ethical Committee of Tokyo Medical and Dental University.

3. Results

3.1. SCEPs after stimulation to the sciatic nerve

In all subjects, SCEPs after sciatic nerve stimulation could be recorded successfully.

SCEPs consisted of conductive polyphasic spike waves (E1) followed by gentle waves. The polyphasic wave propagated from the caudal to the cranial region at a conduction velocity of 60–90 m/s; those waves gradually decreased their amplitude toward cranial region (Fig. 2a).

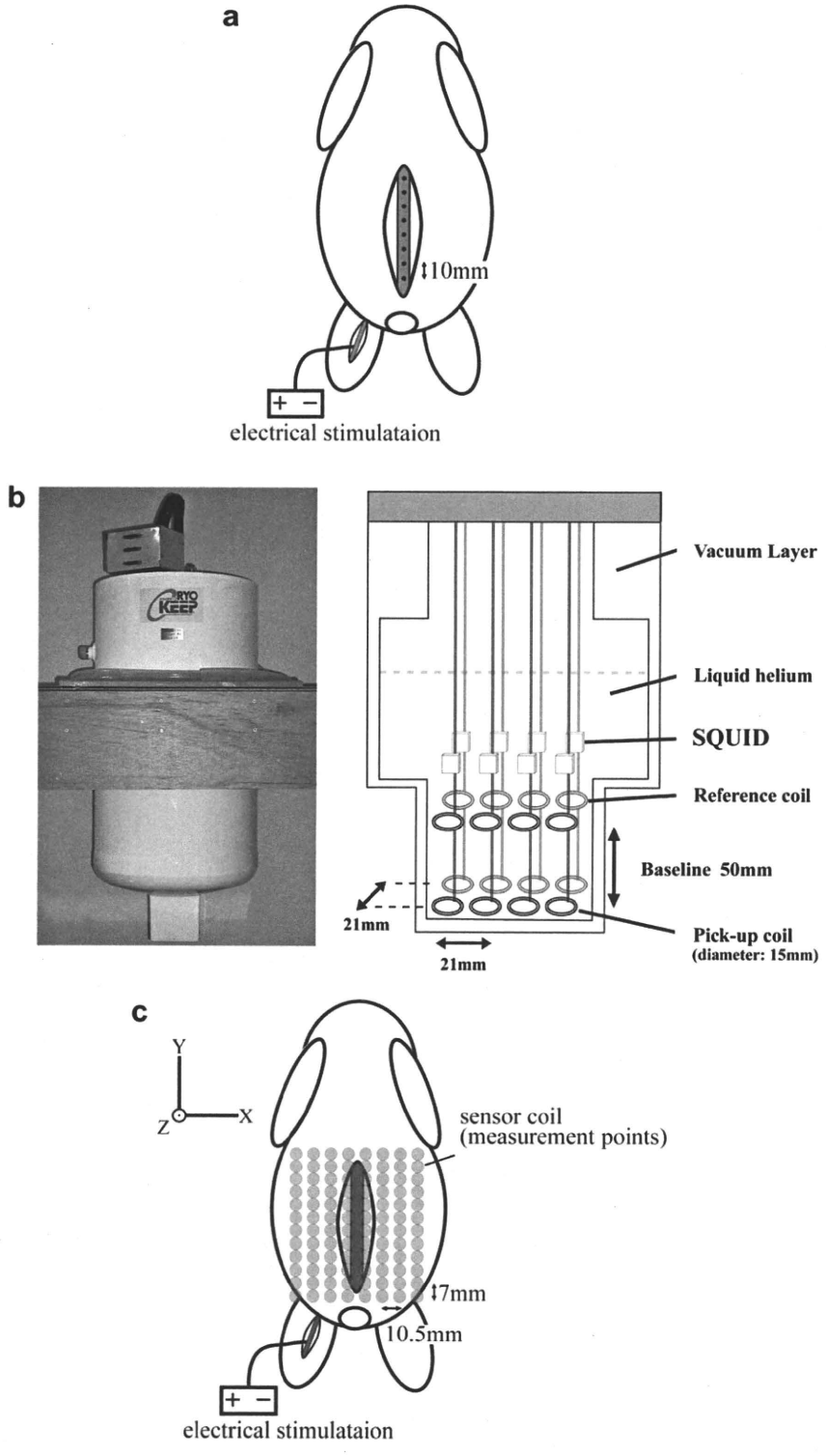

Fig. 1. (a) SCEPs were recorded along the median of the exposed spinal cord after laminectomy by bipolar recording. Each measurement point was spaced 10 mm apart. (b) Our 8-channel SQUID system: subjects were positioned prone just below the dewar on an *X–Y–Z* ordinate stage. Orthogonal elements to the measurement plane of evoked magnetic fields generated around the nerve were able to be detected by pick-up coils. (c) SCEFs were measured over the lumbar spinal cord at about 96 different points (circles) after the electrical stimulation to the sciatic nerve.

The gentle waves (E2) recorded largely around the L6 vertebral level (and not observed above the L4 vertebral level) did not propagate along the spinal cord. The amplitude of E2 decreased when the frequency of the stimulation was increased from 10–60 Hz, whereas the waveform of E1 did not change (Fig. 2b).

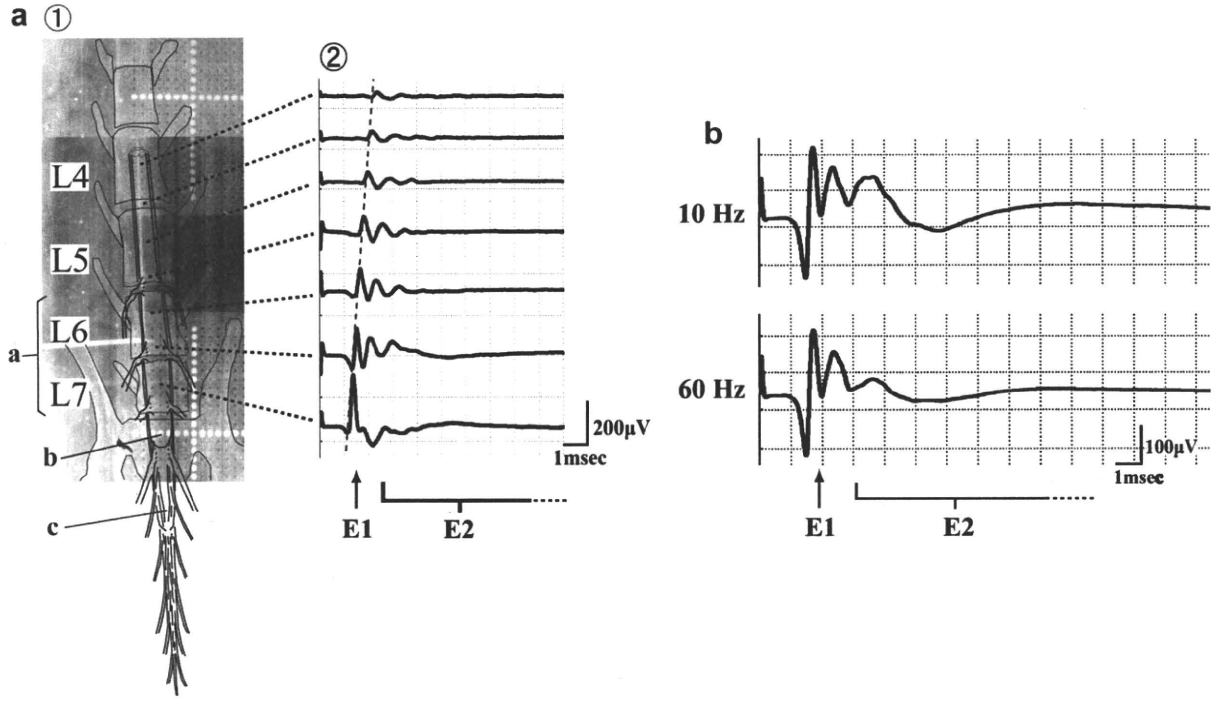

Fig. 2. (a) ① Anterior–posterior view of X-ray image and schematic representation of spinal cord and nerve roots in the lumbosacral spine of rabbit. a, Lumbar enlargement; b, conus medullaris; c, cauda equina. ② SCEPs recorded after sciatic nerve stimulation. E1, conductive polyphasic spike waves; E2, static gentle waves. The polyphasic spike waves propagated toward the cranial region, and later gentle waves were recorded. The largest was noted around the L6 vertebral level, and did not show propagation along the spinal cord. (b) Waveforms of SCEPs at the L6 vertebral level; the amplitude of E2 decreased under high frequency stimuli, whereas E1 did not change its waveform.

3.2. SCEFs after stimulation to the sciatic nerve

In all subjects, SCEFs after sciatic nerve stimulation could also be recorded.

Fig. 3a shows one of the results of the waveform arrangement of the SCEF after left sciatic nerve stimulation based on the measurement points. The signal above the baseline indicates outflux magnetic flow from ventral to dorsal, and the signal below the baseline indicates influx magnetic flow from dorsal to ventral.

Obtained magnetic fields also consisted of polyphasic spike waves (M1) and the following gentle waves. The spike waves showed biphasic configurations; the first deflection of the magnetic signals at the left side of the spinal cord was directed outward, and that of the right side was directed inward. The polarity reversed for the second deflection. Those waves propagated to the cranial region at a conduction velocity of 60–100 m/s.

The following gentle waves (M2), characterized by low amplitude and long duration, were recorded as the largest at about the L6 vertebral level. The amplitude of these waves decreased when high frequency stimuli were applied to the sciatic nerve (Fig. 3b).

The isomagnetic field maps of SCEFs (Fig. 4a) showed a quadrupolar pattern, and these quadrupolar fields propagated from the caudal to the cranial region with a short latency time. Just after this leading magnetic field passed, at least four dipolar fields emerged one by one. At first, a dipolar field appeared at about the L6 vertebral level; the next emerged at about the L5 vertebral level instead of the disappearance of the first dipolar field. Subsequently, the third arose at about the L4 level instead of the disappearance of the second field. After the third dipolar field disappeared, the last one emerged and was sustained for a long duration at the same position as the first. Each dipolar field emerged and disappeared at the same position on the spinal cord without propagation. The direction of the assumed current distribution of each dipolar field looked upward cranially or downward caudally, without uniformity. However, the first and the last fields were in the same direction.

3.3. Estimated current sources

The current sources estimated by the minimum-norm method were visualized and matched to the X-ray image (Fig. 4b). Small arrows indicated the current direction, and the color density in the map indicated the current intensity. A conducting forward and backward current flow, according to the pathway from the nerve roots to the spinal cord, was recognized within a short latency time. Furthermore, volume currents surrounding the intra-axonal currents were also observed. In addition, some stationary currents in turn emerged and disappeared at the different segments one by one. These stationary currents

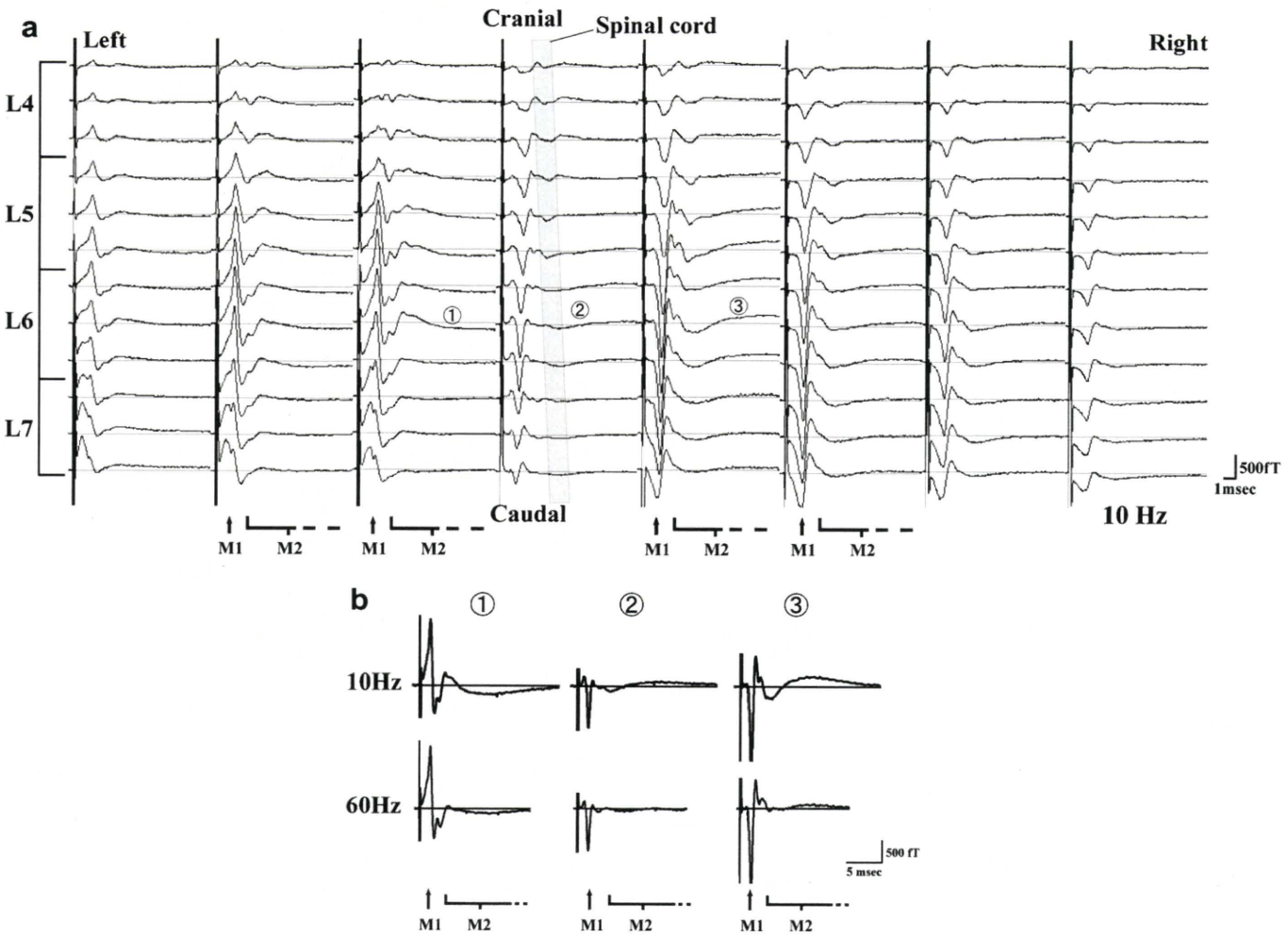

Fig. 3. (a) The waveform arrangement of SCEFs after left sciatic nerve stimulation (10 Hz) based on the measurement points. The gray bar indicates the location of the spinal cord. Some waves consisted of polyphasic spike waves (M1) followed by gentle waves (M2). (b) Some waves were selected to compare the results between 10 Hz and 60 Hz stimulation at the same points in the same subject. The numbers indicate the positions of the waves in (a). The gentle waves (M2) decreased their amplitude, whereas the spike waves (M1) did not change their waveforms under high frequency stimuli.

corresponded to the dipolar fields in the isomagnetic contour map.

4. Discussion

We had previously reported that magnetic fields which were evoked from the spinal cord or peripheral nerve were measurable using our SQUID system, where conductive action potentials were represented as a quadrupolar isomagnetic field pattern and the depolarization corresponded to the center of the quadrupolar fields (Okubo et al., 2003; Fukuoka et al., 2002, 2004).

In this study, we measured magnetic fields around the lumbar spinal cord evoked following sciatic nerve stimulation in order to record and evaluate not only conductive axonal currents but also segmental synaptic activities in the spinal cord.

After electrical stimuli were applied to the sciatic nerve of the rabbit, axonal currents propagated along the nerve and diverged to the L6–S2 nerve roots in the lumbosacral plexus (Barone et al., 1973). Some axonal impulses, after flowing into the spinal cord, would climb up the ascending tracts in the dorsal column to the cranial region and some impulses would switch the axons by synaptic transmission in the dorsal horn and climb up the ipsilateral or contralateral ascending fibers in the white matter. Regrettably, physiological and electrophysiological detailed analysis of the dorsal horn or root potentials of the rabbit were not found in the literature, however, we assumed the constitution of the spinal cord of rabbit was similar to that of cats or rats (Bernhard, 1953; Eccles et al., 1962; Shimoji et al., 1977; Patrick and Malcolm, 1997).

In the segmental-SCEPs, after peripheral nerve stimulation, two different types of potentials could usually be recorded – the spike wave in the short latency followed by gentle and long lasting waves. The spike wave was thought to be derived from the action potentials of the primary afferent of the nerve root and the axonal currents in the white matter, and the following gentle waves originated from synaptic activities in the gray matter of the spinal

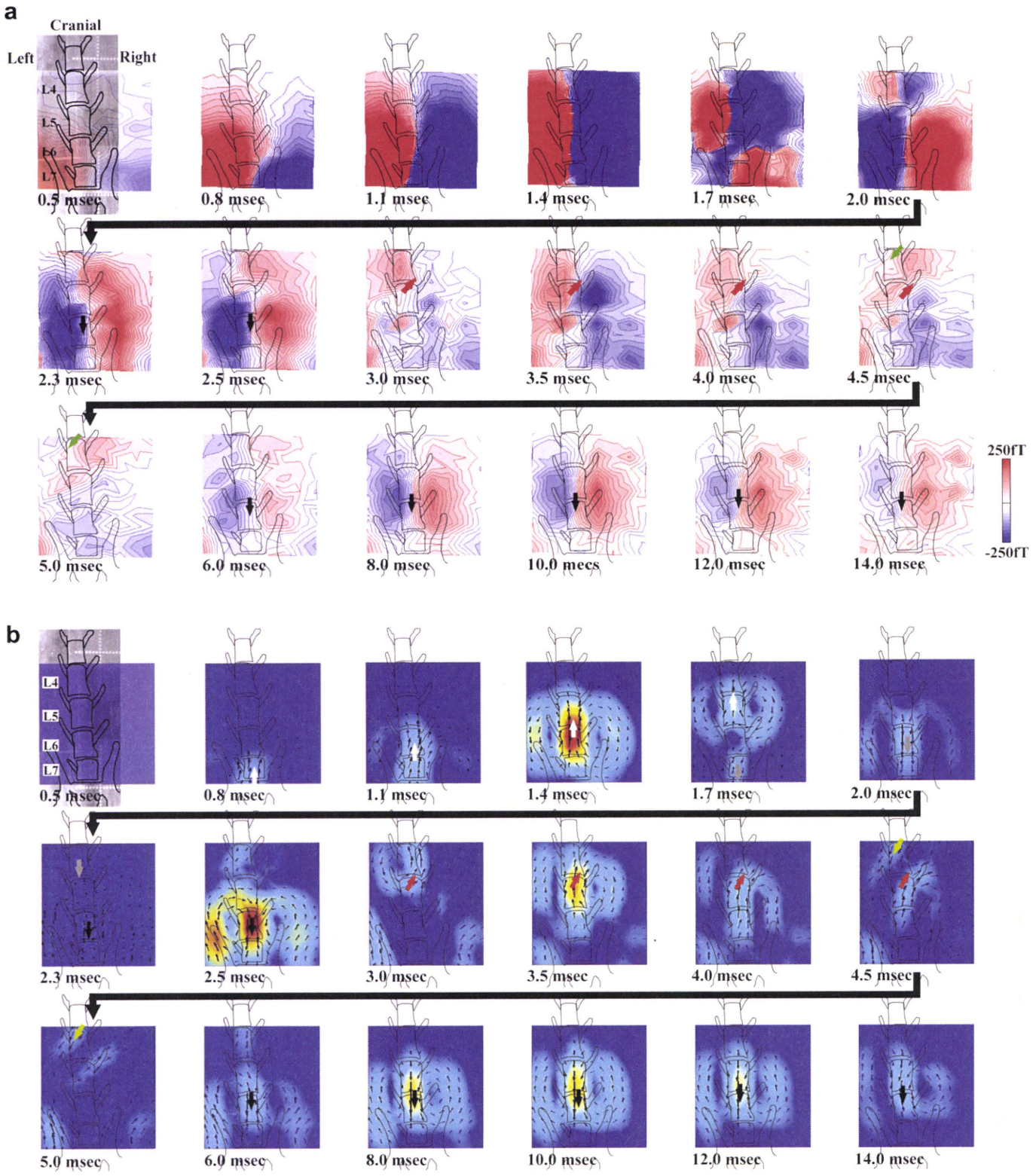

Fig. 4. (a) The isomagnetic field maps of SCEFs; the red color indicates outflux magnetic flow from ventral to dorsal, and the blue color indicates influx magnetic flow from dorsal to ventral. A quadrupolar magnetic field propagated from caudal to cranial within a short latency time (0.8–2.3 ms) almost according to the neural pathway. Just after the quadrupolar magnetic field passed, some stationary and sustained dipolar fields emerged and faded away at a different segment. Initially, one dipolar field emerged at the L6 level (black arrows), the next one appeared at the L5 level (red) in turn; the third one emerged at the L4 level (green), and the last one appeared again at the L6 level (black). (b) Estimated current sources. Propagating intra-axonal currents, forward (white arrows) and backward (gray arrows) current flows and volume currents (surrounding small black arrows) were recognized within a short latency time (0.8–2.3 ms). After the propagating currents, some stationary and sustained currents emerged and faded away at the different segments one by one. Initially, one current source emerged at the L6 level (black arrows), the next one appeared at the L5 level (red), the third emerged at the L4 level (green), and the last one appeared again at the L6 level (black).

cord. Because the spike wave reflects action potentials, it shows propagation along the axonal pathway toward the cranial region. The amplitude of the spike wave is less influenced by the frequency of the stimulation, whereas the gentle waves do not propagate and decrease their amplitude with high frequency stimulation because of synaptic fatigue (Ertekin, 1976; Cracco, 1973; Saiki, 1979; Shimoji et al., 1972). In our experiment, E1 showed polyphasic configurations probably reflecting plural axonal currents. This could possibly be due to differences in nerve root length or the conductivity of each neural fiber in the spinal cord.

In this study we observed two different types of magnetic signals: propagating sharp waves in the short latency time and stationary gentle waves in the late latency time.

Comparing the results of the recorded SCEPs and SCEFs within the same subject, the latency of E1 in SCEPs and M1 in SCEFs at the center of the quadrupolar magnetic fields was nearly the same at the same vertebral level, and similarly, the latency and duration of E2 in SCEPs almost corresponded to that of M2 in SCEFs (Fig. 5). In addition, the conduction velocity of E1 and M1 was close at around 60–100 m/s, which is reasonable for the physiological value of neural conduction velocity (Akaike, 1973; Fukuoka et al., 2002). In the isomagnetic field maps, unlike the propagating quadrupolar fields, the dipolar fields sustained their position and, similar to E2 in SCEPs, they became unclear when high frequent stimuli were applied. Though the complicated volume currents by vertebral structures and gaps of them have a possibility to affect segmental magnetic events, removing dorsal bony interruption by lumbar laminectomy would decrease the effects of these volume currents. Thus, the quadrupolar field was considered to be constructed from M1 and was generated from the primary afferent nerves and the white matter, while the dipolar fields were thought to be constructed from M2 and originated from synaptic activities.

Two different types of estimated current sources, the conductive current flow and stationary currents, would support this conclusion. The forward and backward current flow, corresponding to the quadrupolar magnetic field in the latency, would account for the intra-axonal current flow derived from the action potential propagating from the sciatic nerve to the spinal cord. The following stationary and sustained currents, which emerged and faded away spontaneously, corresponded to the location of the dipolar fields, respectively. The minimum-norm estimation is a popular method for estimating the current distribution in the human brain from MEG data. We adopted this method to estimate current sources. Visualized current sources helped us to better understand simultaneous and adjacent phenomenon more easily.

In most of the subjects, the isomagnetic fields and the estimated currents showed that apparently plural static current sources emerged at different levels on the spinal cord.

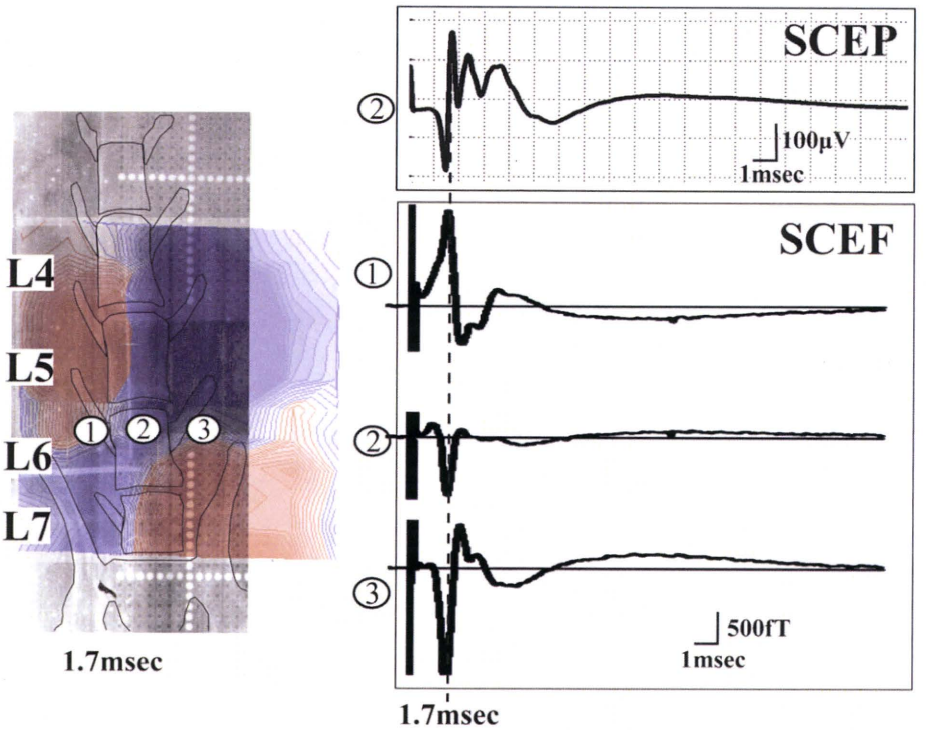

Fig. 5. Isomagnetic contour maps of the quadrupolar pattern and stationary dipolar fields were projected on the X-ray image. When comparing the results of the measurements of SCEP and SCEF at about the L6 vertebral level, the latency of the spike wave in SCEP (1.7 ms) corresponded to that of the center of the quadrupolar magnetic field. This indicates that the quadrupolar magnetic field was generated from the primary afferent. The latency and duration of the following gentle waves in both SCEP and SCEF were also the same, indicating that stationary and sustained dipolar fields were derived from synaptic activities.

Neuromagnetic recordings were thought to be able to visualize axonal activities in the sciatic nerve which flowed into the spinal cord from L6 to S2 nerve roots, climbing up the spinal tracts and activating synaptic transmissions at L6, L5 and L4, in order. The difference in the nerve root length which diverged from the sciatic nerve would reflect the order of appearance of each segmental synaptic activity. The last sustained dipolar field, fired at about the L6 level, indicates that the main segment of sciatic nerve of a rabbit may exist at around the L6 level.

The direction of the synaptic currents did not show uniformity. Although our system is not suitable to measure vertical elements of currents because pick-up coils are placed horizontal to the X–Y plane and designed to measure only orthogonal elements of evoked magnetic fields, further analysis to examine current directions on the Y–Z or X–Z plane would be required for rational explanation of the incoherent synaptic current directions.

In the case of clinical use, stimulation of the peripheral nerve has a great advantage compared with stimulation of the spinal cord using an epidural catheter electrode because peripheral nerves are easily stimulated non-invasively from the skin. The ultimate aim of neuromagnetic recordings is to evaluate the function or the lesion level of the spinal cord without using invasive techniques. The measurement of segmental-SCEFs could become a helpful method to evaluate both the function of multi-segmental synaptic activities and conductive axonal activities in the spinal cord at one time.

Acknowledgements

We gratefully acknowledge the technical assistance of Dr. Y. Adachi from Kanazawa Institute of Technology and Dr. K. Sekihara from Tokyo Metropolitan University.

References

Adachi Y, Miyamoto M, Kawai J, Uehara G. Measurement of spinal cord evoked magnetic fields by vector SQUID biomagnetometer. Electr Eng Jpn 2006;157(2):15–23.

Akaike T. Comparison of neuronal composition of the vestibulospinal system between cat and rabbit. Exp Brain Res 1973;18(4):429–32.

Barone R, Pavaux C, Blin PC, Cuq P. Atlas d'anatomie du lapin. Paris: Masson et Cie; 1973.

Bernhard CG. The spinal cord potentials in leads from the cord dorsum in relation to peripheral source of afferent stimulation. Acta Physiol Scand (Suppl.) 1953;106:1–29.

Cohen D. Magnetoencephalography: detection of magnetic fields produced by alpha rhythm currents. Science 1968;161:778–86.

Cracco RQ. Spinal evoked response: peripheral nerve stimulation in man. Electroencephalogr Clin Neurophysiol 1973;35:379–86.

Eccles JC, Kostyuk PG, Schmidt RF. Central pathways responsible for depolarization of primary afferent fibres. J Physiol 1962;161:237–57.

Ertekin C. Studies on the human evoked electrospinogram. I: The origin of the segmental evoked potentials. Acta Neurol Scand 1976;53:3–20.

Fukuoka Y, Komori H, Kawabata S, Ohkubo H, Shinomiya K, Terasaki O. Imaging of neural conduction block by neuromagnetic recording. Clin Neurophysiol 2002;113:1985–92.

Fukuoka Y, Komori H, Kawabata S, Ohkubo H, Shinomiya K. Visualization of incomplete conduction block by neuromagnetic recording. Clin Neurophysiol 2004;115:2113–22.

Hashimoto I, Mashiko T, Mizuta T, Imada T, Iwase K, Okazaki H. Visualization of a moving quadrupole with magnetic measurements of peripheral nerve action fields. Electroencephalogr Clin Neurophysiol 1994;93:459–67.

Iwaki S, Ueno S. Weighted minimum-norm source estimation of magnetoencephalography utilizing the temporal information of the measured data. J Appl Phys 1998;83:6441–3.

Kawabata S, Komori H, Mochida K, Ohkubo H, Shinomiya K. Visualization of conductive spinal cord activity using a biomagnetometer. Spine 2002;27:475–9.

Klein A, Leeuwen P, Hoormann J, Gronemeyer D. Magnetoneurographic registration of propagating magnetic fields in the lumbar spine after stimulation of the posterior tibial nerve. J Neural Eng 2006;3:125–31.

Mackert BM, Curio G, Burghoff M, Marx P. Mapping of tibial nerve evoked magnetic fields over the lower spine. Electroencephalogr Clin Neurophysiol 1997;104:322–7.

Mackert BM, Burghoff M, Hiss L, Trahms L, Curio G. Tracing of proximal lumbosacral nerve conduction – a comparison of simultaneous magneto – and electroneurography. Clin Neurophysiol 2001a;112:1408–13.

Mackert BM, Burghoff M, Hiss L, Nordahn M, Marx P, Trahms L, et al. Magnetoneurography of evoked compound action currents in human cervical nerve roots. Clin Neurophysiol 2001b;112:330–5.

Matsuura K, Okabe Y. Selective minimum-norm solution of the biomagnetic inverse problem. IEEE Trans Biomed Eng 1995;42(6):608–15.

Okubo H, Komori H, Kawabata S, Fukuoka Y, Shinomiya K. Estimation of localization of neural activity in the spinal cord using a biomagnetometer. J Med Dent Sci 2003;50(2):177–82.

Patrick D, Malcolm L. Five sources of a dorsal root potential: their interactions and origins in the superficial dorsal horn. Am Physiol Soc 1997:860–71.

Saiki K. Spinal evoked potential obtained by stimulation on the median nerve – experimental and clinical studies. J Jap Orthop Ass 1979;53:1893–913.

Sekihara K, Nagarajan SS, Poeppel D, Marantz A, Miyashita Y. Reconstructing spatio-temporal activities of neural sources using an MEG vector beamformer technique. IEEE Trans Biomed Eng 2001;48(7):760–71.

Sekihara K, Sahani M, Nagarajan SS. Localization bias and spatial resolution of adaptive and non-adaptive spatial filters for MEG source reconstruction. Neuroimage 2005;25:1056–67.

Sekihara K, Hild KE, Nagarajan SS. A novel adaptive beamformer for MEG source reconstruction effective when large background brain activities exist. IEEE Trans Biomed Eng 2006;35(9):1755–64.

Shimoji K, Kano T, Higashi H, Morioka T, Henschel EO. Evoked spinal electrogram recorded from epidural space in man. J Appl Physiol 1972;33:468–71.

Shimoji K, Matsuki M, Shimizu H. Wave-form characteristics and spatial distribution of evoked spinal electrogram in man. J Neurosurg 1977;46:304–13.

Trahms L, Erné SN, Trontelji Z, Curio G, Aust P. Biomagnetic functional localization of a peripheral nerve in man. Biophys J 1989;55:1145–53.

A simple performance test for quantifying the severity of cervical myelopathy

N. Hosono,
H. Sakaura,
Y. Mukai,
T. Kaito,
T. Makino,
H. Yoshikawa

From Osaka Kosei-nenkin Hospital, Osaka, Japan

We evaluated 30 patients with cervical myelopathy before and after decompressive surgery and compared them with 42 healthy controls. All were asked to grip and release their fingers as rapidly as possible for 15 seconds. Films recorded with a digital camera were divided into three files of five seconds each. Three doctors independently counted the number of grip and release cycles in a blinded manner (N1 represents the number of cycles for the first five-second segment, N2 for the second and N3 for the third). N2 and N3 of the pre-operative group were significantly fewer than those of the control group, and the post-operative group's results were significantly greater than those of the pre-operative group. In the control group, the numbers decreased significantly with each succeeding five-second interval (fatigue phenomenon). In the pre-operative myelopathy group there was no significant difference between N1 and N2 (freezing phenomenon).

The 15-second test is shown to be reliable in the quantitative evaluation of cervical myelopathy. Although it requires a camera and animation files, it can detect small changes in neurological status because of its precise and objective nature.

■ N. Hosono, MD, PhD, Orthopaedic Surgeon, Division Chief
■ Y. Mukai, MD, PhD, Orthopaedic Surgeon, Advising Doctor
■ T. Kaito, MD, PhD, Orthopaedic Surgeon, Fellow
■ T. Makino, MD, Orthopaedic Surgeon, Fellow
Department of Orthopaedic Surgery
Osaka Kosei-nenkin Hospital, Fukushima 4-2-78, Osaka 553-0003, Japan.

■ H. Sakaura, MD, PhD, Orthopaedic Surgeon, Assistant Professor
■ H. Yoshikawa, MD, PhD, Orthopaedic Surgeon, Professor and Chairman
Department of Orthopaedics
Osaka Graduate School of Medicine, Yamadaoka 2-2, Suita 565-0871, Japan.

Correspondence should be sent to Dr N. Hosono; e-mail: hosono-n@umin.net

©2008 British Editorial Society of Bone and Joint Surgery
doi:10.1302/0301-620X.90B9.20459 $2.00

J Bone Joint Surg [Br] 2008;90-B:1210-13.
Received 7 November 2007; Accepted after revision 24 April 2008

The outcome of patients with a compressive myelopathy can be measured using various scales of severity, such as that of Nurick,[1] Harsh et al[2] and Cooper and Epstein,[3] or the Japanese Orthopaedic Association (JOA) score.[4,5] However, these are of low sensitivity, with few and generally arbitrary categories, any of which may cover a large range of severity. In addition, a subjective scale based on patients' symptoms may be coloured by their general psyche and how urgently they feel the need for treatment. Objective measures are needed to make a proper assessment of surgical treatment.

A simple quantitative walking test was proposed by Singh and Crockard,[6] but this needs space; also, the test has limited value, not only for mildly affected patients, whose walking is often normal, but also for those most severely affected, who cannot walk unaided.

It is well known that finger clumsiness precedes other weaknesses in myelopathy.[7] Ono et al[7,8] proposed a performance test which measures the number of finger grips and releases performed as fast as possible in ten seconds. Although the test is simple and requires only a watch with a second hand, it is not widely used, mainly because its reliability has not been validated. In order to establish the reliability of the test and to facilitate repeated and objective evaluation of finger movement, we recorded finger movements with a digital camera, and extended the test to 15 seconds to allow possible changes of movement to be observed over three five-second intervals.

Patients and Methods

We studied 30 patients, all with MRI evidence of cervical cord compression who had been admitted for decompressive surgery and used 42 patients admitted for hip or knee joint replacement as a control group. No patient had previous history or symptoms of a cervical disorder, nor any systemic disease such as rheumatoid arthritis or cerebral palsy. First, with their right palm pronated, each patient was asked to fully grip and release their fingers as fast as possible. This was then repeated with the left hand. The movements were recorded from an anterolateral direction by a digital camera (DSC-F505V, Sony Corp., Tokyo, Japan) in 'movie' mode. The recording began from the second grip to avoid the motion lag from the cue to the start of movement. The field of view was restricted to the hand and forearm, so that the recordings could be evaluated blindly at a later date. In the myelopathy group the test was performed pre-operatively and then repeated two weeks after a unilateral opening laminoplasty,[9] which achieved successful decompression on

Table I. The intraclass correlation coefficient (ICC) and 95% confidence interval (95% CI) for each phase of the 30 myelopathy patients

	ICC (95% CI)	
	Right hand	**Left hand**
Pre-operative (s)		
0 to 5	0.995 (0.989 to 0.998)	0.991 (0.983 to 0.996)
5 to 10	0.996 (0.992 to 0.998)	0.993 (0.986 to 0.996)
10 to 15	0.986 (0.973 to 0.993)	0.990 (0.979 to 0.995)
Post-operative (s)		
0 to 5	0.991 (0.982 to 0.996)	0.991 (0.984 to 0.996)
5 to 10	0.992 (0.985 to 0.996)	0.979 (0.961 to 0.990)
10 to 15	0.987 (0.975 to 0.994)	0.982 (0.964 to 0.991)
Mean	0.989 (0.979 to 0.996)	

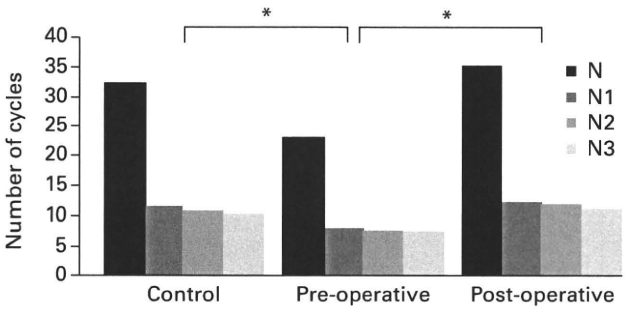

Fig. 1

Barchart showing N, N1, N2 and N3 in each group. N, N1, N2 and N3 were significantly lower in the pre-operative myelopathy group than in the control group (*t*-test, $p < 0.0001$), and were significantly greater in the post-operative myelopathy group than in the pre-operative myelopathy group (* paired t-test; = $p < 0.0001$).

MRI in all cases. The control group performed the test before their arthroplasty.

From the original movie file, five-second segments were abstracted individually by a technician (TM) to create a first, second and third file. Each was slowed to half speed and numbered randomly using a computer-generated random table. As right and left finger movement were recorded separately there were 360 ($2 \times 3 \times 30 \times 2$) five-second files for the myelopathy group and 252 ($2 \times 3 \times 42 \times 1$) for the control group. These 612 files were evaluated independently in a blinded manner by three experienced spinal surgeons (NH, HS, YM). The number of grip and release cycles was counted in increments of 0.5, from a fully open to a fully closed hand, or *vice versa*. For each five-second file, the average of the three examiners' numbers was used, with N1 representing the average number of grip and release cycles for the first file, N2 for the second and N3 for the third. The total number of grip and release cycles over 15 seconds (N) was the sum of N1, N2 and N3. The patients' neurological status was evaluated using the JOA score pre-operatively and two weeks post-operatively, and the correlation of their JOA scores with the sum of their right and left grip cycles was analysed. The protocol was approved by the institutional review board of the hospital and informed consent was obtained from all patients.

The inter-observer reliability of the 15-second test was examined by determining the intra-class correlation coefficient[10] and 95% confidence interval (CI)[11] using data obtained from the pre- and post-operative myelopathy patients. The data were divided according to the time of recording, laterality and phase (first, second, and third five-second segments), so that they could be studied independently. All analyses were performed using SAS 9.1 (SAS Institute Inc., Cary, North Carolina).

Results

The inter-observer reliability of counting the number of grip and release cycles was high (intra-class correlation coefficient 0.989 (95% CI 0.979 to 0.996), Table I). All values are reported as a mean and SD. The overall N was 32.5 (SD 9.0) in the control group, 22.9 (SD 8.7) in the pre-operative myelopathy group, and 34.9 (SD 7.6) in the post-operative myelopathy group. It was significantly lower in the pre-operative group than in the control group (*t*-test, $p < 0.0001$) and significantly greater in the post-operative than in the pre-operative group (paired *t*-test, $p < 0.0001$). There was no significant difference in N between the control and post-operative groups (*t*-test, $p = 0.07$). N1, N2 and N3 were 11.3 (SD 3.3), 10.9 (SD 3.1) and 10.4 (SD 2.8), respectively in the control group; 7.8 (SD 3.1), 7.7 (SD 3.0) and 7.4 (SD 2.7), respectively in the pre-operative group; and 12.0 (SD 2.8), 11.8 (SD 2.5) and 11.2 (SD 2.3), respectively in the post-operative group. The values of N1, N2 and N3 were significantly lower in the pre-operative than in the control group (*t*-test, $p < 0.0001$) and significantly greater in the post-operative than in the pre-operative group (paired *t*-test, $p < 0.0001$, Fig. 1).

In the control group, N2 was significantly lower than N1, and N3 was also significantly lower than N2 (paired *t*-test, Bonferroni adjustment, $p < 0.0001$, Fig. 2). This indicates a significant reduction in the number of cycles in each successive five-second period and appears to be the result of finger fatigue. Conversely, in the pre-operative myelopathy group, N1 and N2 were not significantly different (paired *t*-test, Bonferroni adjustment, $p = 0.15$), whereas N3 was significantly lower than N2 (paired *t*-test, Bonferroni adjustment, $p = 0.0002$, Fig. 3). The lack of a significant difference between N1 and N2 seems to indicate that, at the beginning of the test, myelopathy patients cannot open or close their fingers at their maximum velocity, as though their fingers are frozen. However, in the post-operative myelopathy group the fatigue phenomenon occurred between N1 and N2 (paired *t*-test, Bonferroni adjustment, $p < 0.0001$), as well as between N2 and N3 (paired *t*-test, Bonferroni adjustment, $p = 0.0143$), similar to the control group (Fig. 4).

In the myelopathy group, the JOA score improved significantly from 10.2 (SD 2.7) pre-operatively to 14.2 (SD 2.1) (paired *t*-test, $p < 0.0001$) post-operatively, with no patients deteriorating thereafter. There was a significant positive

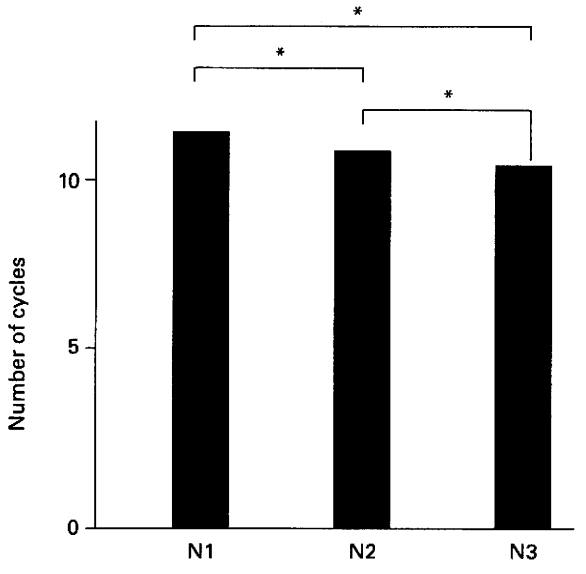

Fig. 2

Barchart showing N1, N2 and N3 in the control group. The number of grip and release cycles decreased significantly with each five-second segment, indicating finger fatigue (* paired *t*-test, Bonferroni adjustment, $p < 0.0001$).

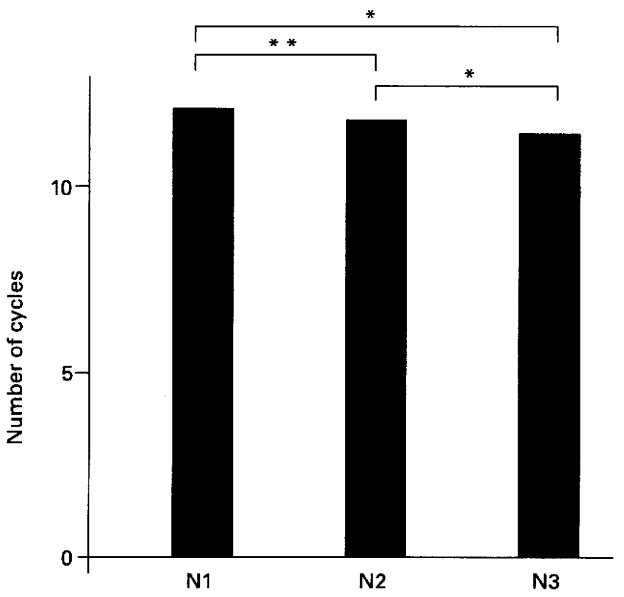

Fig. 4

Barchart showing N1, N2 and N3 in the post-operative myelopathy group. As in the control group, the fatigue phenomenon was observed between N1 and N2, as well as between N2 and N3 (* paired *t*-test, Bonferroni adjustment, $p < 0.0001$; ** $p = 0.0143$).

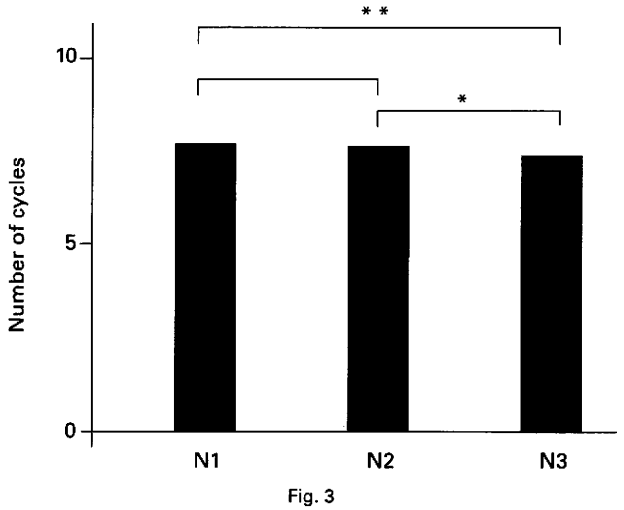

Fig. 3

Barchart showing N1, N2 and N3 in the pre-operative myelopathy group. No significant difference was observed between N1 and N2 in the pre-operative myelopathy patients, indicating that they could not open and close their fingers with maximum velocity at the beginning of the movement. (* paired *t*-test Bonferroni adjustment, $p < 0.0001$; ** $p = 0.0002$).

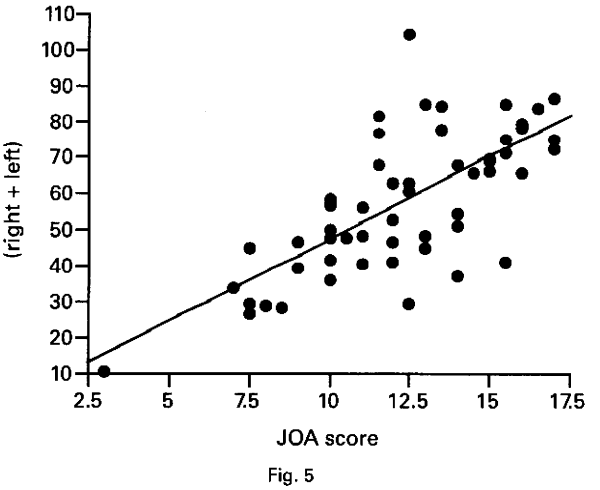

Fig. 5

Graph showing Japanese Orthopaedic Association (JOA) score *vs* N (right + left). There was a significant positive correlation between the JOA score and the sum of the right and left N (Pearson's correlation coefficient was 0.715 ($p < 0.0001$).

correlation between the JOA score and the sum of the right and left Ns (Pearson's correlation coefficient 0.715, $p < 0.0001$, Fig. 5).

Discussion

Ono et al[8] noted that healthy subjects could complete more than 20 grip and release cycles in 10 seconds. Although the test exclusively assesses finger movement, some authors have indicated a significant correlation between the results of this test and other disease severity scales, which evaluate not only motor but also sensory functions in the extremities and trunk.[12,13] In this study, there was significant correlation between the 15-second test and the JOA score ($r = 0.715$). This can be explained by the fact that most

JOA score parameters are associated with a pyramidal tract disorder of the spinal cord, which includes impaired finger movement. As a method for evaluating myelopathy, the ten-second test has advantages over scoring systems. It can be done anywhere, at any time, whereas scoring systems require an experienced rater to improve their reliability.[5] Furthermore, the ten-second test is a reproducible,[14] quantitative assessment, whereas scoring systems are semi-quantitative, with no statistical basis for the points assigned to each section. The ten-second test can be done hourly to detect slight changes in neurological status; consequently, a patient's daily worsening pre-operatively or improvement post-operatively can be evaluated in detail. Despite these merits, the reliability of the ten-second test has not been statistically validated, thus it is not widely used. In this study, we demonstrated the high reliability of the video-recorded 15-second test, with an inter-observer intra-class correlation coefficient of 0.989. At the beginning or end of each five-second segment, the patients' fingers were usually between the fully closed and the fully opened positions. Although an inter-observer difference could occur depending on whether the observer considered the fingers to be open or closed, the reliability of the test has been proven statistically.

In healthy controls, the number of cycles decreased every five seconds. This is considered to be because of fatigue caused by the maximal effort required. Conversely, the fatigue phenomenon was not observed between the first and second segments in myelopathy patients pre-operatively, although there was fatigue between the second and third segments. The reduced number of grip and release cycles in the first five seconds was not due to a time lag between the cue and beginning of movement, as the recording was from the second grip. Myelopathy patients could not open or close their fingers with their maximum velocity at the beginning of movement, as though their fingers were frozen. Ishida et al[15] reported that the walking velocity of myelopathy patients was significantly lower over the first three metres than the last three when they were asked to walk 30 m, as required in the walking test of Singh and Crockard.[6] It is interesting that 'freezing' or clumsiness during the initial phase of movement was seen in the upper and lower extremities of myelopathy patients. However, after successful decompression, they showed no 'freezing'. The video-recorded 15-second test is shown to be a reliable method which can quantitatively evaluate the severity of cervical myelopathy. Although the test is less practicable than the ten-second test, and requires a digital camera and animation files, it can detect small changes in neurological status because of its precise and objective nature.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References

1. **Nurick S.** The pathogenesis of the spinal cord disorder associated with cervical spondylosis. *Brain* 1972;95:87-100.
2. **Harsh GR 4th, Sypert GW, Weinstein PR, Ross DA, Wilson CB.** Cervical spine stenosis secondary to ossification of the posterior longitudinal ligament. *J Neurosurg* 1987;67:349-57.
3. **Cooper PR, Epstein F.** Radical resection of intramedullary spine and cord tumors in adults: recent experience in 29 patients. *J Neurosurg* 1985;63:492-9.
4. **Yamauchi H, Hirabayashi K.** Scoring system for cervical myelopathy. *J Jpn Orthop Assoc* 1994;68:490-503 (in Japanese).
5. **Yonenobu K, Abumi K, Nagata K, Taketomi E, Ueyama K.** Interobserver and intraobserver reliability of the japanese orthopaedic association scoring system for evaluation of cervical compression myelopathy. *Spine* 2001;26:1890-4.
6. **Singh H, Crockard HA.** Quantitative assessment of cervical spondylotic myelopathy by a simple walking test. *Lancet* 1999;354:370-3.
7. **Ono K, Ebara S, Fuji T, et al.** Myelopathy hand: new clinical signs of cervical cord damage. *J Bone Joint Surg [Br]* 1987;69-B:215-19.
8. **Ono K, Fuji T, Okada K, et al.** Myelopathy hand and reversibility of cervical myelopathy. *Bessatsu Seikei Geka* 1982;2:10-17 (in Japanese)
9. **Hosono N, Sakaura H, Mukai Y, Ishii T, Yoshikawa H.** En-bloc laminoplasty without dissection of paraspinal muscles. *J Neurosurg Spine* 2005;3:29-33.
10. **Fleiss JL.** Reliability of measurement. In: *The design and analysis of clinical experiments.* New York: Wiley, 1986:1-32 (in Japanese).
11. **Cappelleri JC, Ting N.** A modified large-sample approach to approximate interval estimation for a particular intraclass correlation coefficient. *Stat Med* 2003;22:1861-77.
12. **Nakamura K, Takeshita K, Tanaka T, Seichi A.** Assessment of motor function in cervical myelopathy: the relationship between performance tests and JOA motor function scores. *Jpn J Rehabil Med* 2004;41:625-7 (in Japanese).
13. **Wada E, Yonenobu K.** Myelopathy hand. *Spine & Spinal Cord* 2005;18:573-7 (in Japanese).
14. **Kaito T, Hosono N, Sakaura H, et al.** Test-retest reliability of the 10-second test for patients of cervical myelopathy. *Rinsho Seikei Geka* 2007;42:335-8 (in Japanese).
15. **Ishida K, Tani S, Enoki Y, et al.** Assessment of impaired repetitive movements and starting clumsiness associated with lower limb spasticity in compression myelopathies. *J Jpn Spine Res Soc* 2006;17:97 (in Japanese).

Preservation of the Nuchal Ligament Plays an Important Role in Preventing Unfavorable Radiologic Changes After Laminoplasty

Hironobu Sakaura, MD, PhD, Noboru Hosono, MD, PhD,† Yoshihiro Mukai, MD, PhD,‡ Kazuya Oshima, MD, PhD,* Motoki Iwasaki, MD, PhD,* and Hideki Yoshikawa, MD, PhD**

Study Design: Prospective study.

Objective: To examine whether preservation of the funicular section of the nuchal ligament attached to the C6 and C7 spinous processes could prevent unfavorable radiologic changes such as kyphotic deformity and destabilization at the C6/7 segment, and to investigate possible correlations between adverse radiologic changes and neurologic recovery or incidence of axial neck pain after laminoplasty in patients with cervical spondylotic myelopathy.

Summary of Background Data: Adverse radiologic changes after cervical laminoplasty have been reported to result from detachment of cervical extensor muscles.

Methods: Subjects comprised 37 patients who underwent modified C3-6 laminoplasty. Our procedure preserves the funicular section of the nuchal ligament attached to the C6 and/or C7 spinous processes in addition to all muscles attached to the C2 and C7 spinous processes and the subaxial deep extensor muscles on the hinged side. The funicular section of the ligament attached only to the C7 spinous process was preserved in 18 patients (C7 group). This funicular section attaching both to the C7 and C6 spinous processes was preserved in 19 patients (C6+7 group). Radiologic and clinical data were prospectively collected.

Results: Postoperative loss of lordosis and destabilization at the C6/7 segment were significantly reduced in the C6+7 group compared with the C7 group. As of final follow-up, neurologic recovery was significantly poorer in the 3 patients with kyphosis than in the 34 patients with straight spinal alignment or lordosis. Frequencies of axial pain showed no significant differences between groups. This value did not vary with the differences in sagittal alignment.

Conclusions: These results indicate that the preserved funicular section of the nuchal ligament attached both to the C6 and C7 spinous processes plays an important role in preventing undesirable radiologic changes after laminoplasty.

Key Words: cervical spine/surgery, postoperative complication, nuchal ligament

(*J Spinal Disord Tech* 2008;21:338–343)

Posterior decompression with laminoplasty is a reliable procedure for multilevel cervical compression myelopathy. However, some surgery-associated problems remain yet to be solved are as follows: undesirable postoperative radiologic changes such as kyphotic deformity and segmental instability, axial neck pain, and segmental motor paralysis.[1] Adverse radiologic changes and axial pain after cervical laminoplasty have been reported as mostly resulting from neck muscle disruption, particularly detachment of the muscle insertion to C2 and C7 spinous processes or deep extensor muscles, including the semispinalis cervicis groups.[2–5] Aside from the posterior neck muscles, some surgeons have recently reported that the funicular section of the nuchal ligament, which is a rounded band constituting posterior border and significantly limits flexion of the cervical spine, attaches tightly not only to the C7 spinous process, but also to the longer-type C6 spinous process, and that only the lamellar section of the ligament, which arises from the anterior aspect of the funicular section, loosely attaches to the shorter-type C6 spinous process.[6] Others have subsequently reported that loss of cervical lordosis and destabilization at the C6/7 segment are significantly greater in patients with the longer-type C6 spinous process than in patients with shorter-type C6 spinous process after conventional C3-7 laminoplasty.[7,8] Since September 2002, modified C3-6 open-door laminoplasty has been our standard procedure for almost all patients with cervical spondylotic myelopathy (CSM). Our

Received for publication March 14, 2007; accepted June 18, 2007.

From the *Department of Orthopaedic Surgery, Osaka University, Graduate School of Medicine, Suita; †Department of Orthopaedic Surgery, Osaka Kosei-nenkin Hospital; and ‡Department of Orthopaedic Surgery, Sumitomo Hospital, Osaka, Japan.

No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

Reprints: Hironobu Sakaura, MD, PhD, Department of Orthopaedic Surgery, Osaka University Graduate School of Medicine, 2-2 Yamada-oka, Suita, Osaka 565-0871, Japan (e-mail: sakaurah@ort.med.osaka-u.ac.jp).

Copyright © 2008 by Lippincott Williams & Wilkins

modified procedure preserves the funicular section of the nuchal ligament attached to the C6 and/or C7 spinous processes, in addition to all of the bilateral muscles attached to the C2 and C7 spinous processes and deep extensor muscles attached to the subaxial spinous processes on the hinged side.[9] The purposes of this prospective study were to examine whether preservation of the funicular section of the nuchal ligament attached to the C6 and C7 spinous processes could prevent loss of cervical lordosis and destabilization at the C6/7 segment, and to investigate possible correlations between adverse radiologic changes and neurologic recovery or incidence of axial neck pain after laminoplasty in patients with CSM.

MATERIALS AND METHODS

Between September 2002 and December 2004, all patients with CSM were treated using C3-6 laminoplasty except for those with moderate or severe cervical kyphosis, a single level anterior lesion without narrow spinal canal, or spinal cord compression at the C6/7 and/or lower levels. On the basis of these criteria, 37 patients underwent our modified C3-6 laminoplasty which had been detailed in the previous report,[9] and have been followed-up for >12 months. These 37 patients were segregated into 2 treatment groups according to the findings of the funicular section of the nuchal ligament on preoperative magnetic resonance imaging (MRI); preoperative sagittal T1-weighted MRI showed the funicular section of the nuchal ligament, which was depicted as the very low intensity wide band, attached both to C6 and C7 spinous processes in 19 of the 37 patients (Fig. 1A). This funicular section attaching both to C6 and C7 spinous processes was preserved and also all muscles attached to the C2 and C7 spinous processes and subaxial deep extensor muscles on the hinged side (C6 + 7 group). In the remaining 18 patients, the funicular section of the nuchal ligament attached not to the C6 spinous process but to the C7 spinous process was demonstrated on sagittal T1-weighted MRI before surgery (Fig. 1B). In these 18 patients, the funicular section of the nuchal ligament attached only to the C7 spinous process was preserved in addition to the neck muscles (C7 group). The C6 + 7 and C7 cohorts were comparable with regard to sex ratio, age at time of surgery, severity of myelopathic symptoms, and duration of postoperative follow-up (Table 1). All 37 patients wore a soft collar for the first 2 weeks postoperatively. All underwent follow-up examination at regular intervals, and radiologic and clinical data were prospectively collected. Maximal flexion and neutral and maximal extension were examined on lateral radiographs of the cervical spine taken before surgery and at intervals thereafter. Sagittal alignment of the cervical spine was measured as the C2-7 angle (θ_{C2-7}) formed by 2 lines drawn parallel to the posterior margin of the vertebral body on a radiograph in the neutral position (Fig. 2A). Kyphosis and lordosis were defined as $\theta_{C2-7} \leq -10$ degrees and ≥ 10 degrees, respectively. All other spines were classified as straight. Segmental alignment at the C6/7 level ($\theta_{C6/7}$) was also measured in the same way as θ_{C2-7} (Fig. 2B). Range of motion (ROM) was calculated by subtracting maximal flexion angle from maximal extension angle. Neurologic status was assessed using the Japanese Orthopaedic Association (JOA) score.[10] Axial neck pain was graded as severe (painkillers or local injection regularly needed), moderate (physiotherapy or compress regularly needed), or mild (no treatment needed) in according with a previous report.[5] Severe or moderate pain persisting for >1 week during the first month postoperatively was considered to constitute early axial pain. Severe or moderate pain persisting for >1 month after surgery was considered to constitute late axial pain.[5]

The unpaired t test, Mann-Whitney U test, or Fisher exact probability test was applied for statistical analysis using JMP 5.0.1 software (SAS Institute, Cary, NC), as appropriate. Values of $P < 0.05$ were considered to indicate statistical significance.

TABLE 1. Characteristics for all Patients in the C6+7 and C7 Cohorts

	C6+7 Group	C7 Group	P
No. patients	19	18	
Male:female	16:3	13:5	NS
Age at the surgery (y)	60.2 ± 13.1	66.0 ± 11.0	NS
JOA score before surgery (points)	11.5 ± 2.2	10.2 ± 2.3	NS
Duration of follow-up (mo)	24.3 ± 10.3	23.7 ± 8.5	NS

Mean ± standard deviation.
NS indicates not statistically significant.

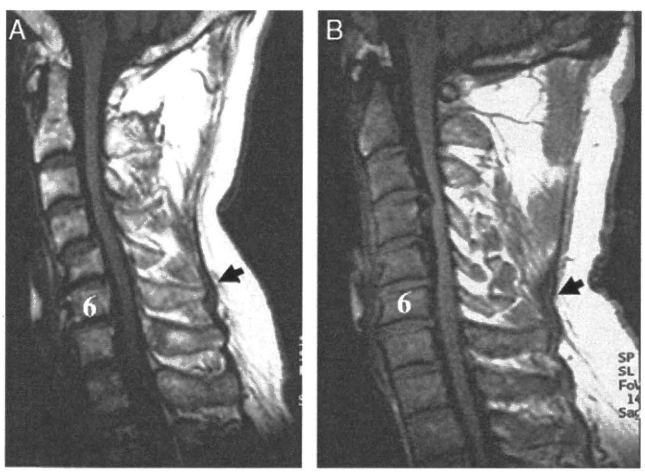

FIGURE 1. Two types of the funicular portion of the nuchal ligament attachment on T1-weighted MRI. A, C6+7 type; the funicular portion of the nuchal ligament attaches both to the C6 and C7 spinous processes. B, C7 type; the funicular portion of the nuchal ligament attaches only to the C7 spinous process.

© 2008 Lippincott Williams & Wilkins

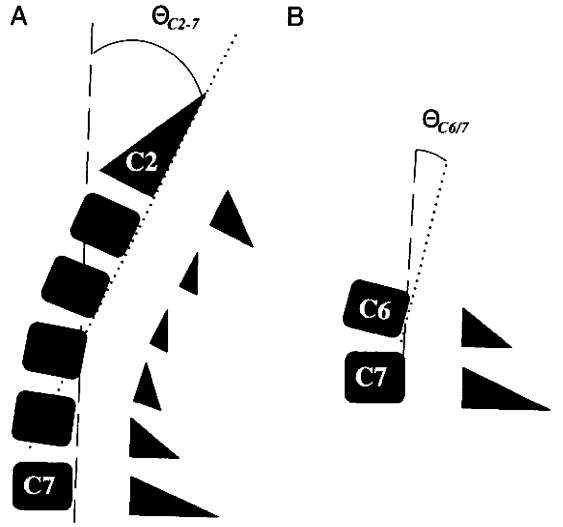

FIGURE 2. Radiologic measurement of the cervical spine. A, Cervical sagittal alignment was measured as C2-7 angle (θ_{C2-7}) formed by 2 lines drawn parallel to the posterior margin of the vertebral body on a radiograph in the neutral position. B, Segmental alignment at C6/7 ($\theta_{C6/7}$) was in the same way as C2-7 angle.

RESULTS

Sagittal Alignment of the Cervical Spine

θ_{C2-7} increased from 13.5 ± 13.2 degrees (mean ± standard deviation) before surgery to 16.2 ± 14.3 degrees at final follow-up in the C6 + 7 group, and decreased from 17.6 ± 12.8 degrees to 14.1 ± 17.0 degrees in the C7 group. Although preoperative θ_{C2-7} showed no significant difference between groups, the mean and standard deviation of changes in θ_{C2-7} within each patient were 2.7 ± 6.2 degrees in the C6 + 7 group, and −3.5 ± 10.1 degrees in the C7 group, respectively (unpaired t test: $P = 0.0318$; Fig. 3). According to our classification, no patients displayed postoperative deterioration of sagittal alignment in the C6 + 7 group (Table 2). Conversely, 5 of 18 patients from the C7 group developed deterioration of sagittal alignment. At the final visit, preoperative lordosis had changed to straight in 3 of the 15 patients and kyphotic deformity had developed in 2 of the 3 patients with straight alignment before surgery (Table 3).

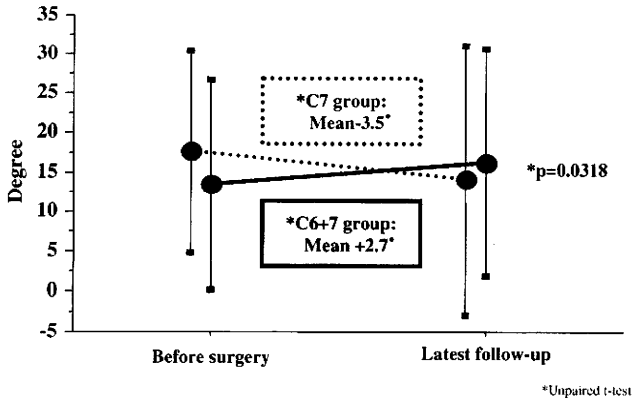

FIGURE 3. Postoperative changes in sagittal alignment. Postoperative loss of C2-7 angle was significantly greater in the C7 group than in the C6+7 group. Mean indicates mean loss of the C2-7 angle.

TABLE 2. Postoperative Changes in Cervical Sagittal Alignment (C6+7 Group; n = 19)

	At the Latest Follow-up		
Cervical Alignment Before Surgery	Lordosis	Straight	Kyphosis
Lordosis	12	0	0
Straight	0	6	0
Kyphosis	0	0	1

Relationship Between Changes in Sagittal Alignment of the Cervical Spine and Neurologic Outcome

At the final visit, 3 patients displayed cervical kyphosis and the remaining 34 patients had straight or lordotic alignment. Mean recovery rate of JOA score in the 3 patients with kyphosis was only 25%, significantly worse than that in the 34 patients with straight alignment or lordosis (64%) (Mann-Whitney U test: $P = 0.0132$; Fig. 4).

Segmental Alignment at the C6/7 Level

$\theta_{C6/7}$ decreased from 7.4 ± 7.0 degrees before surgery to 6.9 ± 7.1 degrees at final follow-up in the C6 + 7 group and from 9.6 ± 4.8 degrees to 6.6 ± 5.2 degrees in the C7 group, respectively. Although preoperative $\theta_{C6/7}$ showed no significant difference between groups, the mean and standard deviation of changes in $\theta_{C6/7}$ within each patient were −0.5 ± 3.1 degrees in the C6 + 7 group, and −2.9 ± 3.2 degrees in the C7 group, respectively (unpaired t test: $P = 0.0317$; Fig. 5).

ROM of the Cervical Spine

C2-7 ROM decreased from 39.9 ± 14.6 degrees before surgery to 28.1 ± 8.2 degrees at final follow-up in the C6 + 7 group and from 35.3 ± 12.7 degrees to 26.7 ± 14.6 degrees in the C7 group, respectively. Segmental ROM at the C6/7 level decreased from

TABLE 3. Postoperative Changes in Cervical Sagittal Alignment (C7 Group; n = 18)

	At the Latest Follow-up		
Cervical Alignment Before Surgery	Lordosis	Straight	Kyphosis
Lordosis	12	3	0
Straight	1	0	2
Kyphosis	0	0	0

© 2008 Lippincott Williams & Wilkins

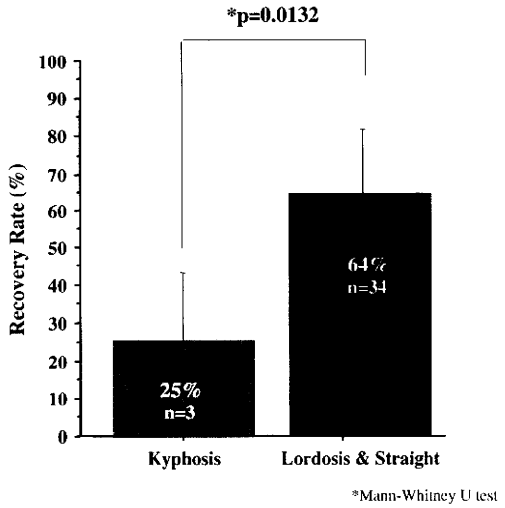

FIGURE 4. Relationship between sagittal alignment of the cervical spine and neurologic recovery. Mean recovery rate of JOA score in the 3 patients with kyphosis was only 25%, significantly worse than in the 34 patients with straight alignment or lordosis.

5.6 ± 3.2 degrees before surgery to 5.1 ± 3.0 degrees at final follow-up in the C6+7 group and from 6.4 ± 4.0 degrees to 4.9 ± 4.2 degrees in the C7 group, respectively. Postoperative loss of C2-7 ROM and C6/7 ROM showed no significant differences between groups.

Axial Neck Pain

Early axial neck pain was identified in 4 patients of the C6+7 group and 3 patients of the C7 group. One patient in each group experienced late axial neck pain (Table 4). Frequencies of early and late axial pain showed no significant differences between groups. This value did not vary with differences in sagittal alignment.

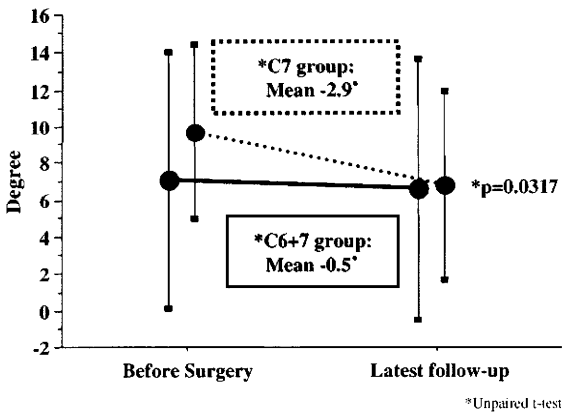

FIGURE 5. Postoperative changes in sagittal alignment at the C6/7 segment. Postoperative loss of the C6/7 angle was significantly greater in the C7 group than in the C6+7 group. Mean indicates mean loss of the C6/7 angle.

TABLE 4. Axial Neck Pain After Surgery

	Early Pain	Late Pain
C6+7 group (n = 19)	4	1
C7 group (n = 18)	3	1
	NS	NS

NS indicates not statistically significant.

DISCUSSION

Unfavorable postoperative radiologic changes such as kyphotic deformity remain one of the main problems associated with cervical laminoplasty,[1] as loss of lordosis can lead to worse neurologic outcomes.[11] Ratliff and Cooper,[1] in their review of cervical laminoplasty, identified postlaminoplasty deterioration of cervical alignment in approximately 35% of their patients, with development of cervical kyphosis in approximately 10%. However, the majority of previous reports have displayed some significant problems, such as patient populations including multiple etiologies of the cervical spine such as spondylosis and ossification of the longitudinal ligaments. Furthermore, study design has typically been retrospective.[1,12,13] Aita et al[14] reported that loss of lordosis after laminoplasty in patients with CSM was greater than that in patients with ossification of the longitudinal ligaments, and conversely, loss of ROM changed with sagittal alignment of the cervical spine. Therefore, in the current study, disease etiology of the patient population was unified. Focusing attention on CSM, deterioration of sagittal alignment after laminoplasty developed in approximately one third of patients and loss of C2-7 angle reached 30% to 60% of preoperative angle.[14–16] These unfavorable changes have been assumed to have mostly resulted from disruption of the facet joints and neck muscles, particularly detachment of the muscle insertion to the C2 spinous process and deep extensor muscles, including the semispinalis cervicis groups.[2–4,13,14,16] Some surgeons have recently reported that preservation of these extensor muscles provides reduced loss of lordosis after surgery compared with conventional laminoplasty.[2–4]

Aside from confirming these extensor muscles as important dynamic stabilizers of the cervical spine, a recent biomechanical study proved that the nuchal ligament represents a significant restraint on cervical spine flexion. Range of flexion increased to 28% and tangent stiffness decreased to 27% compared with the intact cervical spine after resection of the nuchal ligament.[17] Kobayashi et al[6] recently reported that the funicular section of the nuchal ligament attaches tightly to the longer-type C6 spinous process in addition to the C7 spinous process, as can be clearly depicted on T1-weighted MRI. Muramoto et al[7,8] subsequently reported that both loss of lordosis and destabilization at the C6/7 segment were significantly greater in patients with the longer-type C6 spinous process than those with the shorter-type C6 spinous process after conventional C3-7

© 2008 Lippincott Williams & Wilkins

laminoplasty in patients with CSM. On the basis of those results, they concluded that the funicular section of nuchal ligament attached both to the C6 and C7 spinous processes should be preserved in cervical laminoplasty.[7,8] However, whether the preserved funicular section of the nuchal ligament attached to C6 and C7 spinous processes could prevent adverse postoperative radiologic changes was unclear. No previous studies have examined radiologic changes after laminoplasty in which the funicular section of the nuchal ligament attached to the C6 and/or C7 spinous processes was preserved.

In the present study, our modified C3-6 laminoplasty in patients with CSM preserved the funicular section of nuchal ligament attached to the C6 and/or C7 spinous processes as along with all muscles attached to the C2 and C7 spinous processes and the subaxial deep extensor muscles on the hinged side. The only difference in surgical procedures between the C6 + 7 and C7 groups was that the funicular section of nuchal ligament attached to the C6 spinous process was preserved in the C6 + 7 group. As a result, mean θ_{C2-7} increased to 120% of preoperative angle in the C6 + 7 group. The C6 + 7 group had increased lordosis as compared with the preoperative state, whereas cervical lordosis usually somewhat decreased after laminoplasty. We speculate that this finding might be resulted from increased tension of the nuchal ligament after C3-6 open-door laminoplasty with preservation of the funicular section of nuchal ligament attached both to the C6 and C7 spinous processes. Although preservation of the cervical extensor muscles would contribute to the maintenance of lordosis after surgery, these results indicate that preservation of the funicular section of nuchal ligament attached both to the C6 and C7 spinous processes plays an important role in preventing loss of lordosis. The relationship between adverse changes in sagittal alignment and neurologic recovery has not always been clearly demonstrated in previous reports.[1] However, Suda et al[11] reported that loss of lordosis led to poorer neurologic outcomes. In fact, recovery rate of JOA score in 3 patients with kyphosis was significantly poorer than that in the remaining 34 patients with straight alignment or lordosis in the present study. Taken together, preserved funicular section of the nuchal ligament attached both to the C6 and C7 spinous processes can contribute to reduced loss of lordosis and better neurologic outcomes.

With regard to destabilization at the C6/7 segment, mean postoperative loss of $\theta_{C6/7}$ was 0.5 degrees in the C6 + 7 group and 3.0 degrees in the C7 group in the present study. Sasai et al[16] reported that loss of segmental alignment at the C6/7 level averaged 5.3 degrees after conventional C3-7 laminoplasty in patients with CSM. Although preservation of the subaxial deep extensor muscles on the hinged side would contribute to maintenance of stability at the C6/7 segment, these results show that the preserved funicular section of nuchal ligament attached to the C6 and C7 spinous processes plays a central role in preventing postoperative C6/7 segmental destabilization. Our modified C3-6 laminoplasty for CSM provides sufficient decompression of the encroached spinal cord and greatly reduced incidence of axial neck pain.[5] However, whether neurologic problems might occur at the C6/7 level due to progression of degenerative changes remains a matter of concern for long-term follow-up. In light of the results that mean postoperative loss of $\theta_{C6/7}$ was only 0.5 degrees in the C6 + 7 group, preservation of the funicular section of the nuchal ligament attached both to the C6 and C7 spinous processes would become one measure for preventing neurologic deterioration owing to degenerative changes at the C6/7 segment.

The limitation in the present study is that the patients were segregated into 2 treatment groups according to the findings of the funicular section of the nuchal ligament on preoperative MRI without complete randomization of treatment. Although Kobayashi et al[6] reported that the funicular section of the nuchal ligament attaching tightly to the C6 and/or C7 spinous processes can be clearly depicted on T1-weighted MRI, there might be some differences between findings of the funicular section of the nuchal ligament depicted on MRI and true anatomies. Therefore, further study is needed to clarify the accuracy of the findings of the nuchal ligament on MRI. The randomized controlled study is also needed to examine whether the preserved funicular section of the nuchal ligament attached both to the C6 and C7 spinous processes could prevent adverse postoperative radiologic changes without any potential biases, which could have been introduced with our selection criteria in the present study.

REFERENCES

1. Ratliff JK, Cooper PR. Cervical laminoplasty: a critical review. *J Neurosurg*. 2003;98(3 suppl): 230–238.
2. Iizuka H, Shimizu T, Tateno K, et al. Extensor musculature of the cervical spine after laminoplasty: morphologic evaluation by coronal view of the magnetic resonance image. *Spine*. 2001;26: 2220–2226.
3. Shiraishi T, Fukuda K, Yato Y, et al. Results of skip laminectomy-minimum 2-year follow-up study compared with open-door laminoplasty. *Spine*. 2003;28:2667–2672.
4. Takeshita K, Seichi A, Akune T, et al. Can laminoplasty maintain the cervical alignment even when the C2 lamina is contained? *Spine*. 2005;30:1294–1298.
5. Hosono N, Sakaura H, Mukai Y, et al. C3-6 laminoplasty takes over C3-7 laminoplasty with significantly lower incidence of axial neck pain. *Eur Spine J*. 2006;15:1375–1379.
6. Kobayashi N, Fujiwara J, Kitagawa T, et al. The nuchal ligament (in Japanese). *J Jpn Spine Res Soc*. 2004;15:168.
7. Muramoto A, Inoue H, Satoh T, et al. Morphology of the C6 spinous process and its effect on alignment and flexibility of the cervical spine after laminoplasty (in Japanese). *J Jpn Spine Res Soc*. 2005;16:150.
8. Muramoto A, Inoue H, Ohsawa Y. Morphology of the C6 spinous process and cervical range of motion after laminoplasty (in Japanese). *J Jpn Spine Res Soc*. 2006;17:251.
9. Hosono N, Sakaura H, Mukai Y, et al. En bloc laminoplasty without dissection of paraspinal muscles. *J Neurosurg Spine*. 2005; 3:29–33.

© 2008 Lippincott Williams & Wilkins