Intraoperative Motor and Sensory Monitoring of the Cauda Equina

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A SET OF standard techniques to monitor the motor and sensory function of the cauda equina is proposed for surgery in the lumbosacral spinal canal for the release of a tethered cord or the removal of a neoplasm. Continuous loudspeaker-controlled recording of electromyographic activity in four leg muscles of both sides supplied the surgeon with immediate feedback on injury to any of the motor roots from the second lumbar to the fourth sacral segment. Continuous recording of tibial nerve somatosensory evoked potentials yielded information about the functional state of parts of the lumbosacral sensory pathways. Motor roots could be identified by electrical stimulation in the operating field with bipolar stimulation forceps and recording of compound muscle action potentials from the leg muscles. Sensory nerve roots could be identified by nerve root somatosensory evoked potentials recorded from the scalp after the electrical stimulation of the exposed nerve. This set-up is a combination of previously developed monitoring techniques and provides the surgeon with functional information: 1) continuous feedback on the state of the endangered motor and sensory function of the cauda equina; and 2) rapid anatomical identification of nerve roots and their distinction from fibrous or neoplastic structures. (Neurosurgery 34:702–707, 1994)

Key words: Cauda equina, Electromyography, Electrophysiological monitoring, Evoked potentials, Laminectomy, Spine

Neurosurgical procedures in the lumbosacral spinal canal for the release of a tethered cord or the removal of a tumor carry a substantial risk of new or increased postoperative neurological deficit. The anatomical situation is frequently difficult to oversee because the cauda equina, the filum terminale, and the spinal cord may be displaced by tumor tissue, lipoma, or scar formation. Even dissection under the microscope may not suffice to identify neural structures that should be preserved and tumorous or tethering structures that should be removed or transsected. Urological and electrophysiological techniques have been applied to monitor procedures involving parts of the cauda equina, the conus, or the lumbosacral spine: continuous recording of electromyographic (EMG) activity in sphincter muscles (12), recording of compound muscle action potentials (CMAPs) from leg (14, 21) and sphincter (11, 14, 21) muscles to electrical stimulation in the operating field, direct sensory evoked potential recording from roots to electrical stimulation in the periphery (4), measurement of sphincter tone and bladder pressure (18, 21). In the recent past, multimodality monitoring packages became widely available and applied. A comprehensive monitoring strategy that balances the possible versus the necessary monitoring modalities in this field remains to be defined. The rationale of such a monitoring set-up is that the patient needs maximal security concerning the risk of postoperative, iatrogenically induced neurological deficits, especially because many present with minimal symptoms and surgery is indicated to halt progression (19).

To accomplish these goals, neurophysiology has to offer the surgeon two different tools: first, continuous monitoring of the motor and sensory roots and, second, immediate identification of structures as functional nervous tissue, and their distinction from fibrous or neoplastic structures. Both are provided by the standard set-up proposed here.

PATIENTS AND METHODS

Eighteen patients (12 female, 6 male; 6 to 74 yr) with tethered cord (n = 7) or intraspinal lumbosacral neoplasms (n = 11) underwent surgery and were monitored. The patients were placed in the prone position, laminectomy was performed at the pertinent level, and microsurgical technique was used throughout.

Stimulation and recording

The stimulation and recording parameters are summarized in *Table 1*. Two independently working EMG machines (Sensor

TABLE 1. Stimulation and Recording Parameters[a]

Parameter	Motor Monitoring		Sensory Monitoring	
	Muscle Activity	Motor Root Neurography	Tibial Nerve SSEP	Nerve Root SSEP
Stimulation electrode		Forceps	Surface electrodes	Forceps
Stimulation intensity		1–10 mA	30 mA	1–10 mA
Stimulus duration		0.2 ms	0.5–1 ms	0.5 ms
Stimulus frequency		Single or 1/s	5/s	5/s
Averages	Free run	None	512	128
Recording	Leg and sphincter muscles (right versus left)	Leg and sphincter muscles (right versus left)	Cz' - Fz Th 12–L 1	Cz' - Fz Th 12–L 1
Filter bandpass	32–800 Hz	32–800 Hz	30–600 Hz	30–600 Hz
Input gain	20 μV/U	0.1–2 m V/U	10 μV/U	10 μV/U

[a] **SSEP, somatosensory evoked potentials.**

94a and MS 6; Medelec Ltd., United Kingdom) with four channels each were used simultaneously, one for the motor and one for the sensory part. Furthermore, one machine was interfaced to a personal computer (Apple II GS). The Munich group used an eight-channel Viking II device with a DOS-operated intraoperative monitoring software package (Nicolet Instruments Inc., WI). Custom-made platinum wire needle electrodes 2 to 3 cm long were used for scalp recording of somatosensory evoked potentials (SSEPs) and for muscle recording of the lower limb and sphincter muscles. Subdermal needle electrodes were preferred to surface electrodes in order to avoid problems with electrode fixation and surface resistance. Isolated EMG electrodes 5 cm long (DISA, Denmark) were used for spinal recording of SSEPs. The tibial nerve was stimulated by surface electrode pairs with proximally placed cathodes and interelectrode distances of 2.5 cm. Stimulations in the operating field were made with isolated bipolar stimulation forceps with bare tips (GK 675; Aeskulap, Germany) with an isolated current stimulator, after the operation field had been dried and made free of blood or cerebrospinal fluid to avoid current spread (15, 21). Constant current square wave impulses were used throughout.

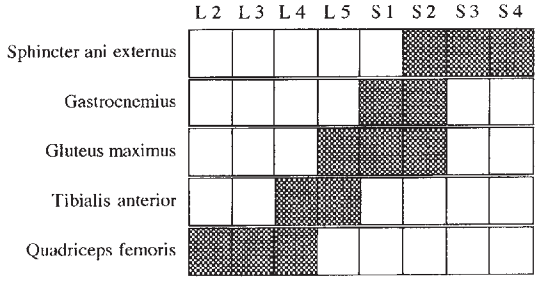
Anesthesia and preparation

After placement of stimulation electrodes over the tibial nerves, anesthesia was induced with thiopental-sodium. Intubation was performed under the short-acting muscle relaxant pancuronium bromide. Then, the recording electrodes were placed on the scalp, spine, and muscles. Anesthesia was maintained with halothane (0.5 vol%) and fentanyl (0.045 to 0.3 μg/kg/min); the patients breathing 30% oxygen and 70% nitrous oxide without further muscle relaxation (20).

Detailed monitoring procedure

Continuous recording of electromyographic activity

With recording of the quadriceps femoris, tibialis anterior, gluteus maximus, and sphincter ani externus muscles, all segments from L2 to S4 were continuously under scrutiny (*Fig. 1*) (23). To spare recording channels, recordings were obtained from the right versus the left side, i.e., the active electrode was inserted over the right, and the "reference" electrode was inserted over the corresponding left muscle. The recording unit was connected to a loudspeaker yielding immediate acoustic feedback to the surgeon, a technique that is commonly used for motor cranial nerve monitoring (9, 10, 15). Motor unit potentials and neurotonic discharges, elicited by the manipulation of or injury to nerve roots, e.g., by simple contact, traction, compression, transsection, or coagulation, were recorded (*Fig. 2*) (1, 15, 16).



	L2	L3	L4	L5	S1	S2	S3	S4
Sphincter ani externus						▨	▨	▨
Gastrocnemius					▨	▨		
Gluteus maximus				▨	▨	▨		
Tibialis anterior			▨	▨				
Quadriceps femoris	▨	▨	▨					

FIGURE 1. Segmental innervation pattern of the recorded muscles (23).

Continuous monitoring of tibial nerve somatosensory evoked potentials

The tibial nerve was stimulated at the ankle. Recordings were obtained from the scalp (Cz'/Fz, according to the international 10–20 system) and from the spine between the spinous processes of Th12 and L1, if a preoperative examination had proved that cortical responses were recordable at all. These SSEPs yielded information predominantly about the sensory roots of the fifth lumbar and the first sacral segments (23).

The recordings of the initial operation phase, during the approach, served as a baseline for the amplitude and latency of the primary cortical SSEPs. Abolition of the cortical response

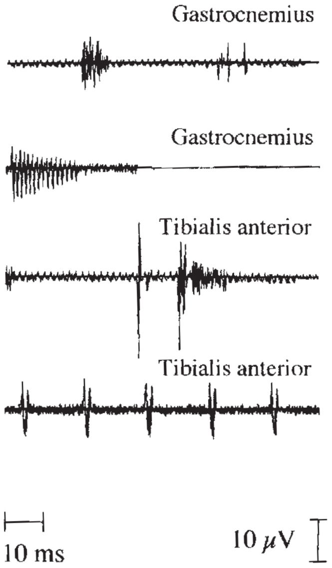


FIGURE 2. Continuous monitoring of motor nerve roots. Recordings were made in free run mode. The first curve shows activity evoked by touching a nerve root (contact activity), the second shows a neurotonic discharge, the third shows contact activity followed by a neurotonic discharge, and the fourth shows repetitive motor unit potentials after a nerve root had been stretched by a retractor.

at 40-ms latency (P40) was considered a significant and serious surgical complication (2, 6, 7) if the response to contralateral stimulation was preserved. Asymmetric loss of the spinal response and of P40 indicates that anesthesiological or cardiovascular problems are unlikely to be the cause of response alteration. Prolongation of P40 latency over the maximal baseline value and amplitude diminution of the P40/N50 response under the minimal baseline value were arbitrarily taken as a sign to alert the surgeon.

Identification of motor nerve roots (lumbosacral motor root neurography)

To identify motor roots, these were stimulated with the forceps with single impulses. Recordings were made via the same electrode installation as for continuous EMG activity recording, but with adapted recording parameters (*Table 1*). At first, CMAPs were searched with relatively high stimulation intensities of about 10 mA, using lower input amplification. If a CMAP was recorded, stimulus intensity was reduced and input gain was increased in order to obtain responses from the target nerve only and to avoid responses elicited by the spread of current to neighboring nerves. *Figure 3* (see below) shows the typical responses evoked in lower limb muscles with a stimulation intensity slightly above the threshold applied to various motor roots in the lumbar spinal canal. The side of the stimulated nerve root was determined surgically but was considered less important because the roots of both sides and all levels had to be preserved.

Identification of sensory nerve roots (lumbosacral root somatosensory evoked potential)

Those structures that were not functional motor roots according to the previous motor neurography were then stimulated directly with SSEP parameters (*Table 1*). Recordings were obtained via the same installation as the tibial nerve SSEPs. *Figure 4* (see below) shows a typical cortical response with its primary positive peak at about 20-ms latency (P20) compared with a normal tibial nerve cortical SSEP. A stimulated structure was verified as a sensory nerve root if a reproducible cortical response with a positive deflection at about 20 ms (P20) could be recorded.

To summarize, if a structure could not be accurately identified anatomically, it was first stimulated to identify motor roots. If no CMAP could be recorded, stimulation and recording for the detection of sensory roots were performed. If no reproducible response was recorded, the stimulated structure was considered to be non-neural or at least nonfunctional.

CLINICAL RESULTS

In this series of 18 cases, there was one transient motor deficit due to deliberate transsection of the nerve root, which had given rise to a neuroma. No other postoperative, new neurological deficit concerning motor, sensory, and sphincter function was observed. The following case descriptions illustrate the practical situation in cauda equina monitoring.

Patient 1

A 42-year-old man was admitted with sciatic pain and sensory deficit at L5 and S1 on the right side caused by an intradural root neuroma at L5 with foraminal and extraforaminal extension. Because the foramen at L5 was only slightly enlarged, it was decided to resect the lesion via a combined interlaminar fenestration and extraspinal approach, thus leaving the facet joint at L5–S1 intact. This small approach offered only restricted visual control over the intraforaminal course of the L5 root and the neuroma. Therefore, a physiological control was indispensible to avoid damaging the root. Dissection and traction of the tumor were guided by the presence or absence of EMG discharges (*Fig. 2*). The tumor was entirely removed without postoperative sensory or motor deficit.

Patient 2

A laminectomy was performed on a 19-year-old man for a sacral intradural ganglioneuroma. Neurotonic discharges were noted shortly after tumor dissection had begun. Motor stimulation identified neural tissue intermingled with the fibrous elements of the neoplasm. On the basis of this information, it was decided that tumor resection was definitely impossible without damage to several nerve roots and subsequent neurological deficits. After a biopsy, the wound was closed. The patient had no postoperative deficit and was successfully treated with radiotherapy. Two years after the procedure, the patient is doing well and has no clinically apparent tumor growth.

Patient 3

A 41-year-old man was admitted with transient sphincter dysfunction and weakness of the legs. A tethered cord syndrome was diagnosed. After exposure, continuous EMG recording showed only minimal manipulation-evoked activity and no sustained repetitive discharges. This indicated that the dissection was close to the motor

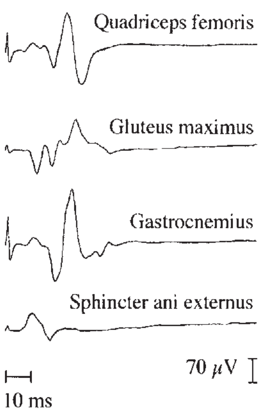


FIGURE 3. Selective identification of motor nerve roots (cauda equina neurography). CMAPs recorded from four muscles after the selective stimulation of various motor roots at intensities slightly above threshold.

roots but again assured the surgeon that the procedure was still safe. Direct stimulation with CMAP and SSEP recording helped in the identification of motor roots, sensory roots, and the filum terminale before the latter was transsected (see *Figs. 3 and 4*). Cortical tibial nerve SSEPs on both sides ranged from 39 to 43 ms in latency without apparent correlation to procedure steps. There was no apparent impairment of the monitored sensory pathways, and the release of the stretched cord had no immediately measurable effect on sensory function (*Fig. 5*). The postoperative neurological examination remained unchanged.

DISCUSSION

The ideal neuromonitoring in cauda equina surgery should be a 1) technique that provides immediate warning to the neurosurgeon whenever he or she touches or injures neural tissue before irreversible injury has occurred, and 2) one that would enable the surgeon immediately to identify structures in the operating field and differentiate between functional nervous tissue and fibrous structures.

Therefore, several functional modalities have to be monitored more or less simultaneously. From the many hardware and software possibilities now available and widely applied, the appropriate modalities for each surgical situation need to be selected on the basis of anatomical and physiological considerations that take into account the requirements of the surgical situation. The proposed set of cauda equina monitoring seeks a compromise between the possible and the necessary.

By taking advantage of the muscle as a natural amplifier of the motor unit's electrical activity, continuous EMG recording techniques were elaborated initially for cranial motor nerve monitoring, particularly in facial nerve surgery (1, 5, 9, 10, 15, 16). This report shows that the same technique can be applied for continuous motor root monitoring in the lumbosacral spinal canal. With continuous EMG recording, bursts or trains of motor unit potentials or repetitive neurotonic discharges elicited by injury to the peripheral motor nerve or nerve root (*Fig. 2*) have been identified as indicators of postoperative transient or permanent neurological deficit (1, 10). The predictive value of these "manipulation-evoked" discharges is based on experience and empirical information rather than on controlled studies or on detailed understanding of the pathophysiology. There seems to be a difference between activity that terminates with the cessation of manipulations and activity that is sustained thereafter. At least, the sustained and usually repetitive activity seems to have something in common with EMG phenomena that occur in neurotonia (22) and myokymia (3). However, the intraoperatively recordable discharges still await thorough analysis to investigate this assumption. For practical purposes—and our results and experience support this notion—continuous EMG recording is a reliable tool that approaches the above-mentioned monitoring ideal.

The sensory system is different in that single-current discharges that may be elicited by injuring or touching the nerve are too small to be recorded along their ascending pathways in a clinical situation. Immediate information on injury to sensory nerve roots is therefore not available. SSEPs to stimulation of the tibial nerve are an established technique for continuous sensory spinal cord monitoring (2, 6, 7). However, this technique has the disadvantage of being always one step behind because of the time gap between injury and measurable conduction changes. Moreover, for anatomical reasons, tibial nerve stimulation covers predominantly the L5 and the S1 roots (23) and leaves the higher and lower segments at least partly unmonitored. Although, in this series, no complication arose from this shortcoming, filling this gap would be desirable. Therefore, the additional use of pudendal (8) or dermatomal (17) SSEPs could be considered especially because newer monitoring machines provide more recording channels.

The electrophysiological identification of anatomical structures as motor nerve is already an integral part of cranial nerve surgery (5, 9, 10, 15). The results of this report and the experience of others (14) show that this straightforward technique is applicable to the cauda equina region to identify the motor nerve roots by single electrical stimulations with a handheld forceps or stimulator (*Fig. 3*).

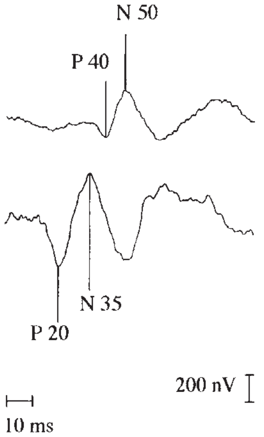


FIGURE 4. Selective identification of sensory nerve roots. Comparison of cortical SSEPs to tibial nerve stimulation (*upper curve*) and to direct sacral nerve root stimulation (*lower curve*). Note the difference of approximately 20 ms between the latencies of the first positive peak, which accounts for the peripheral conduction time.

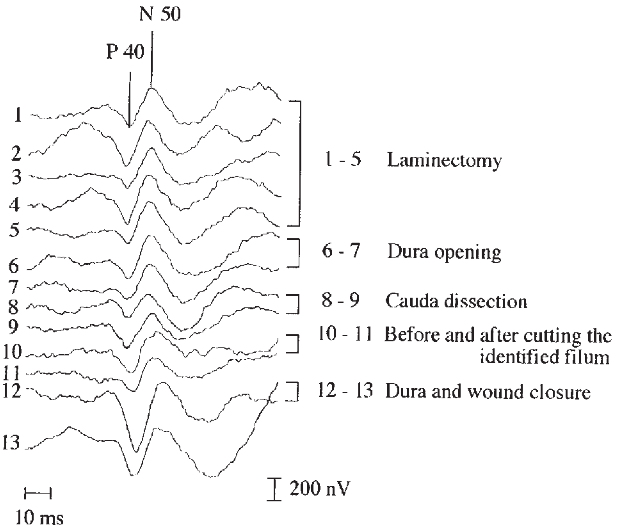


FIGURE 5. Continuous monitoring of the sensory nerve roots. Series of cortical SSEPs recorded after tibial nerve stimulation during the release of a tethered cord. Latencies were stable, and amplitudes remained within baseline limits.

It has been argued that anal sphincter monitoring alone does not suffice to monitor bladder function concomitantly (4, 13). Others have therefore used high-frequency stimulation of the pertinent roots to evoke a tonic contraction of the detrusor muscle. The subsequent increase in bladder pressure was measured with an intravesical urinary catheter connected to a pressure transducer (21). The shortcoming of this technique is that it cannot detect changes that arise from manipulating or damaging the sacral roots, which is possible by the continuous recording of spontaneous EMG activity.

The innervation of both the anal and vesical sphincters as well as the detrusor vesicae arises from the second to the fourth sacral segments (4, 13, 23). By monitoring the sphincter ani externus as pars pro toto, the function of both detrusor and sphincter vesicae is therefore under indirect scrutiny during surgery.

The identification of sensory nerve roots is slightly more complex. This report shows that the stimulation of the nerve root with recording of the cortical SSEPs allows easy and fast identification of functional sensory nerve roots (*Fig. 4*). Peripheral transcutaneous stimulation of the pudendal nerve with recording of dorsal root action potentials in the operating field is also being implemented for this purpose (4). This principle (dermatomal stimulation–intraspinal recording), if applied to all lumbar and sacral roots, would require multiple stimulators to cover all dermatomes bilaterally.

With the proposed cauda equina monitoring set-up, the placement of electrodes and intraoperative stimulation were not time consuming. In the surgeons' view, it saved operating time by allowing more rapid and decisive—and safer—preparation than would be possible on an anatomical basis alone, an impression that is difficult to prove. The clinical results of this report show that the technique proved reliable because the sometimes difficult surgical decisions made on the basis of monitoring did not result in unexpected new neurological deficits.

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COMMENTS

Kothbauer and colleagues used a set of monitoring techniques during surgery in the lumbosacral area for tethered cord release and/or tumor resection. These techniques included posterior tibial nerve and sensory nerve root somatosensory evoked potentials, continuous electromyographic monitoring of lower extremity muscles and the rectal sphincter, and stimulation of motor roots with electromyographic response for identification purposes (similar to facial nerve monitoring). Eighteen cases were monitored, with no permanent postoperative neurological deficits. Illustrative examples are given to show the utility of each of these techniques. The authors have designed an effective and efficient synthesis of available monitoring techniques, which could help all neurosurgeons improve the results of this type of procedure.

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The technical report by Kothbauer and coworkers highlights the benefit of multimodality monitoring during surgery of the cauda equina. These techniques clearly provide the surgeon with additional information about nerve location, nerve function, and nerve irritation.

In these times of conservation of resources as part of health care reform, it will be important that the value of such techniques be carefully defined and documented. It should be possible to demonstrate whether these techniques indeed can save operative time, anesthesia time, or improve outcomes. This would best be done in a randomized study matching patients undergoing surgery with and without these techniques.

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