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Spinal cord potential recordings from the extradural space during scoliosis surgery†

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Summary

For monitoring spinal cord functions during corrective surgery of scoliosis, we have recorded percutaneously from the posterior extradural space at the C5–7 levels the ascending conducted spinal cord potentials (ASCP) in response to extradural stimulation of the cauda equina in 134 patients. The ASCP consists of three spike-like components (C1, C2 and C3) followed by slow components. The extradurally recorded ASCP were not affected by anaesthetic agents. There were no significant differential effects of spinal distractions on each of the three spike potentials. There were no postoperative neurological abnormalities in patients whose ASCP showed no changes, amplitude increases, amplitude decreases of less than 50% or latency increases (> 0.2 ms) during spinal manipulations (no false negatives, but some false positives). Five patients who suffered postoperative neurological damage exhibited more than 50% changes in amplitude of the ASCP during surgery. All these neurological sequelae occurred in the first 80 patients. In the last 54 patients, in whom the distraction forces on the spine were controlled rapidly by observation of the amplitude changes in ASCP, there were no postoperative neurological abnormalities, except for one patient in whom an accidental spinal cord injury was produced by a hook. The results suggest that the distraction force on the spine must be reduced immediately when the amplitudes of the ASCP decrease by more than 50% of control values with or without latency increases. (*Br. J. Anaesth.* 1994; **73**: 350–356)

Key words

Spinal cord, evoked potentials. Monitoring, evoked potentials. Surgery, spinal.

Neurological deficits after spinal cord or spine surgery pose a serious problem. There have been many attempts to monitor spinal cord function during spine or spinal cord surgery by using somatosensory evoked potentials (SEP) recorded from the scalp [1]. Unfortunately these potentials are susceptible to the effects of anaesthetic agents and vary during the course of anaesthesia and surgery [2–5].

Another method of intraoperative assessment of cord function is the "wake-up" test [6]. However, this provides only an assessment of motor function at a particular moment and not moment-to-moment monitoring of cord function and it may be very unpleasant.

Intraoperative monitoring of spinal cord function using spinal cord potentials (SCP) recorded with extradural catheter electrodes is thought to be reliable, as extradurally recorded ascending conducted SCP (ASCP) remain constant and are almost unaffected by anaesthetic agents [7–10]. In order to prevent spinal cord damage caused by manipulation of the spinal cord or spine, we have been monitoring spinal cord function during surgery using extradural recording [11] which permits simple and safe recording of stable ASCP.

We present a survey of changes in the conducted SCP in order to define the critical values of changes in amplitude and latency caused by surgical manipulation of the spine during scoliosis surgery in relation to postoperative neurological sequelae.

Patients and methods

We studied 134 patients undergoing corrective surgery for scoliosis. The patients were aged 5–57 yr (median age 31 years) (80 females and 54 males). To correct deformities of the spinal column, different procedures were performed (table 1). All 134 patients with scoliosis had no neurological deficits before operation. Each patient and the family gave informed consent for this study which was approved by the Institutional Review Board of our university hospital.

Atropine 0.5 mg, hydroxyzine 1–1.5 mg kg^{-1} and pentazocine 0.75–1 mg kg^{-1} were given i.m. about 40 min before induction of anaesthesia. A cannula was inserted into the cephalic vein for administration

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Table 1 Operations in which ascending conducted spinal cord potentials (ASCP) were monitored in the distraction force-controlled and uncontrolled groups (patients with postoperative neurological deficits)

Operation	*n*	Uncontrolled	Controlled
Harrington rod instrumentation	77	42 (4)	35 (0)
Dwyer's operation	24	17 (0)	7 (0)
Zielke's operation	8	5 (0)	3 (1)
Luque's operation	11	6 (0)	5 (0)
Cotrel–Doubousset's operation	9	6 (0)	3 (0)
Others	5	4 (0)	1 (0)
Total	134	80 (4)	54 (1)

of drugs and infusion of electrolyte solution (lactated Ringer). Anaesthesia was induced with thiamylal sodium 3–5 mg kg^{-1} i.v. A heating blanket was placed under each patient to maintain a constant rectal temperature (36.5–37.5 °C). The depth of anaesthesia during corrective surgery was kept constant and maintained with 60% nitrous oxide–neuroleptanalgesia (70 patients), nitrous oxide–morphine (15 patients), nitrous oxide–enflurane (38 patients), nitrous oxide–halothane (nine patients) or nitrous oxide–isoflurane (two patients). Pancuronium 0.1–0.05 mg kg^{-1} was given i.v. to obtain complete neuromuscular block during operation.

RECORDING METHODS

The procedures used to introduce the catheter electrodes into the extradural space were based on the technique of continuous extradural anaesthesia, developed by Shimoji, Higashi and Kano [11] (fig. 1A). Before induction of anaesthesia, the subjects were placed in the lateral decubitus position and a 16-gauge Tuohy needle was inserted percutaneously into the extradural space via a paramedian approach using "loss of resistance" [12]. After ascertaining that neither blood nor spinal fluid was aspirated, a catheter electrode was inserted through the Tuohy needle to 2–5 cm beyond the bevel rostrally. The catheter electrode comprised a polyethylene tube with three silver electrodes placed 1 cm apart from each other on its tip (fig. 1B). The rostral catheter electrode was located usually at the C6–7 level and the caudal electrodes at the L3–4 levels. Supramaximal electrical pulses (0.1 ms in duration) for component 3 (C3) (20–25 times the threshold strength) for component 1 (C1) (fig. 2) were delivered from a constant current stimulator with an isolation unit. These rectangular pulses (peak current 15–20 mA) in the extradural space did not produce any neurological or histological damage [13, 14]. As the ASCP were small and contaminated easily by ECG artefacts [15, 16], they were obtained at intervals between the T and P waves of the ECG [17–19].

The time constant of the amplifier with high frequency characteristics of more than 20 kHz was set at 2 s and a high pass filter was not used. The averaged responses (n = 10–64) were stored on a floppy disc and photographed or plotted on an X–Y plotter. A radiograph was taken for final confirmation

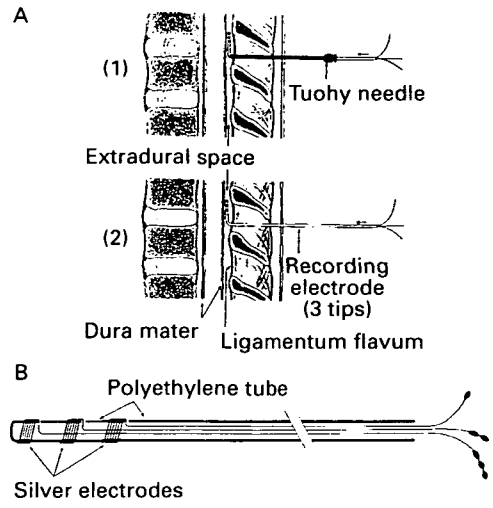

Figure 1 A: Schematic representation of introduction of a catheter electrode into the posterior extradural space, based on the technique of continuous extradural anaesthesia. (1) A catheter electrode is introduced into the posterior extradural space through the Tuohy needle. (2) The Tuohy needle is pulled out, leaving the catheter electrode in the posterior extradural space. B: Structure of the catheter electrode made from a polyethylene tube. Three silver wires (150 mm in diameter) are coiled and attached to the polyethylene tube, 10 mm apart. Their connecting leads run through the tube.

of electrode position in the operating room during surgery or in the recovery room after surgery, or both.

MONITORING PROCEDURES

There were some neurological deteriorations after operation in patients in whom the ASCP decreased in amplitude by more than 50%, with or without an increase in latency (of more than 0.2 ms), during spinal manipulations when the distraction force was not reduced or reduced minimally. Therefore, we controlled the distraction force on the spine in the last 54 patients as follows. When the amplitude of the ASCP (the first component) decreased by less than 30% during distraction, the surgical manipulations were continued without interruption. However, when the amplitude of the ASCP decreased by more than 50% with or without an increase in latency (of more than 0.2 ms) during manipulations, the distraction force was reduced by 3 kg stepwise at 3-min intervals. When the ASCP disappeared with spinal distraction, the traction forces were released immediately and reappearance of the ASCP was awaited.

DATA ANALYSIS

The peak-to-peak amplitudes of the three components (C1, C2, C3) of the ASCP and the initial positive peak latencies were calculated sequentially (see fig. 2). One-way analysis of variance was conducted to identify significant differences in amplitude and latency in the ASCP before, during and after surgical manipulations of the spine. After this analysis, the least significant difference test for multiple comparison was applied when significant

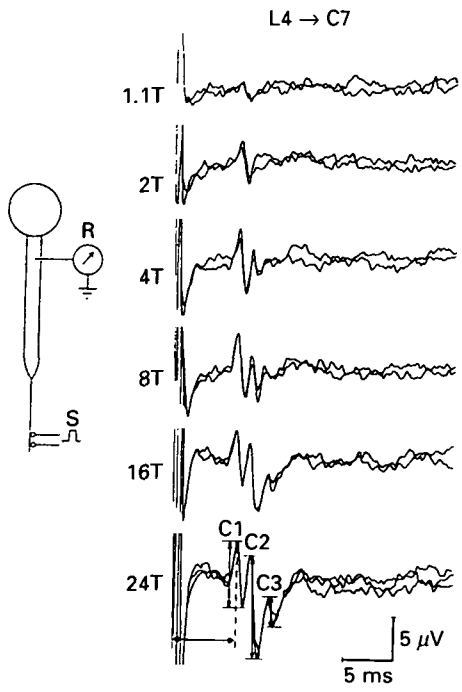

Figure 2 Effect of stimulus intensity on the fundamental pattern of ascending conducted SCP (ASCP) recorded at the C7 vertebral level elicited by cauda equina stimulation at the L4 vertebral level (L4 → C7) in a patient (female, 13 yr old) with scoliosis during neuroleptanaesthesia. Only the first component was seen at twice the threshold strength (2T). The second and third components appeared at 4 (4T) and 8 (8T) times the threshold strength, respectively. Each sweep represents the summation of 25 responses. Two or three sweeps were superimposed. Stimulation (S) and recording (R) arrangements are demonstrated schematically on the left. Upward deflection denotes positivity in this and subsequent figures. Large potential displacement at the start of each sweep denotes the stimulus artefacts in this and subsequent figures.

Table 2 Comparison of amplitudes of the ASCP before anaesthesia, before and during surgical manipulations and after the end of anaesthesia in 81 patients in whom there were no significant changes in the ASCP during surgical manipulations of the spine (mean (SEM))

	Before anaesthesia (%)	Before surgery (%)	During surgery (%)	After anaesthesia (%)
C1	100	99 (2)	102 (1)	99 (3)
C2	100	99 (2)	101 (2)	98 (2)
C3	100	98 (3)	100 (2)	95 (4)

differences were found. Fisher's extract probability test was used to analyse the distribution of patients with postoperative neurological deficits to detect differences between instrumentations and also between the distraction force-controlled and uncontrolled groups. P less than 0.05 was considered statistically significant.

Results

FUNDAMENTAL PATTERNS OF ASCP

In all 134 scoliotic patients, we could obtain ASCP across the area involved. Figure 2 shows the fundamental pattern of the ASCP recorded from the posterior extradural space at the cervical enlargement (C7) in a subject in response to extradural stimulation of the cauda equina (L4). Action potential-like spikes, composed usually of three components, could be recorded, as reported previously [18].

When the subjects were awake or under a light stage of anaesthesia, these three spikes were followed by a slower negative–positive complex (figs 2 and 3). Only the first component was seen with weak stimulation, while the second and third components appeared at a greater stimulus strength (fig. 2). The approximate maximum conduction velocity of the ASCP, measured from the distance between stimulus and recording sites and the peak latency of the C1 component, was mean 81.5 (SEM 4.8) m s^{-1}. The amplitude of the C1 component estimated from the positive peak to the negative peak was 7.2 (1.7) μV at supramaximal stimulation before induction of anaesthesia. These results were similar to our previous data obtained in anaesthetized normal subjects [18]. These three components (C1, C2, C3) of the ASCP showed no significant changes during anaesthesia and also in response to surgical procedures in 81 of 134 patients (table 2). There were no significant differential effects of spinal distractions on each of the three spike-like components (C1, C2, C3) of the ASCP that showed amplitude reduction during surgery (table 3). Later latency slow waves of the ASCP were affected also by operative manipulation (figs 3 and 4), but were not analysed because of their high variability.

RELATIONSHIP BETWEEN ASCP CHANGES AND POSTOPERATIVE NEUROLOGICAL FINDINGS

Changes in the ASCP occurred in 53 of 134 patients during and after surgical manipulations, but not before. Table 4 shows a summary of the relationship between changes in ASCP during corrective surgery and postoperative neurological findings in 134 scoliosis patients. Eighty-one patients with no significant changes in ASCP revealed no neurological

Table 3 Maximum decrease in amplitude in each component of the ASCP (C1, C2, C3) during spinal manipulations in patients with and without neurological sequelae (mean (SEM)). *$P < 0.05$ between groups

	Without neurological sequelae ($n = 31$)			Neurological deficits ($n = 5$)		
	Before (%)	During (%)	P	Before (%)	During (%)	P
C1	100	41 (3)	< 0.01	100	26.4 (9.6)*	< 0.001
C2	100	40 (4)	< 0.01	100	28.3 (9.7)	< 0.001
C3	100	41 (4)	< 0.01	100	27.8 (10.1)	< 0.001

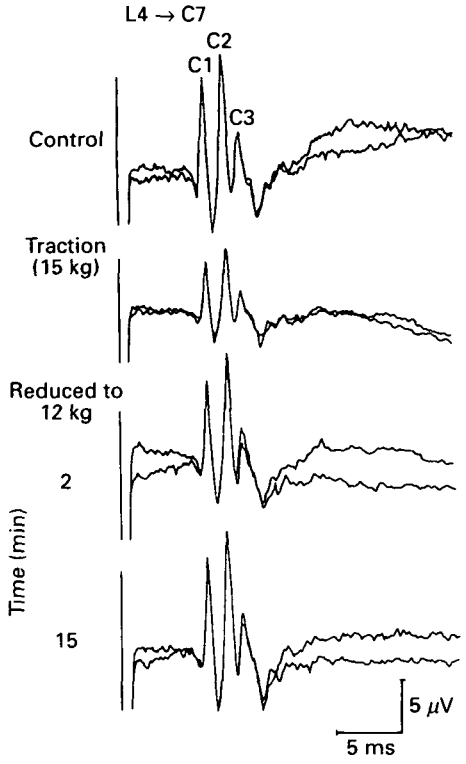

Figure 3 An example of control of distraction force by monitoring the ASCP during spinal surgery in a 26-yr-old female patient with idiopathic scoliosis. The ASCP elicited by stimulation of the cauda equina (L4) was recorded from the cervical enlargement (C7). The amplitude of the polyphasic spikes was reduced suddenly (amplitudes of C1, C2, C3 components decreased to 47%, 47.5%, 49% of control values, respectively) during distraction (Traction) of the spine with 15 kg. These changes in the ASCP recovered within 15 min after reduction of the distraction force to 12 kg.

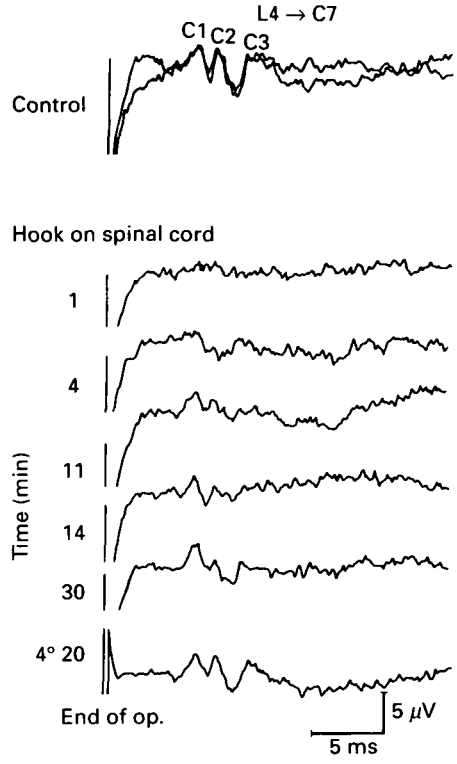

Figure 4 Disappearance of the ASCP by compression with an instrument occurred during Zielke's operation in a 14-yr-old male patient with idiopathic scoliosis (patient No. 5 in table 5). The ASCP was recorded from the cervical enlargement (C7) in response to stimulation of the cauda equina (L4). The SCP disappeared suddenly on accidental application of a hook on the left side of the spinal cord during removal of the disc between L1 and T12. Four minutes after the accident, the ASCP reappeared, but the amplitudes did not return fully to the control values even at the end of operation (C1, 72%, C2 70%, C3 70% of control, 4 h after the accident). The patient suffered from postoperative monoplegia of the injured side which gradually recovered over three months.

deficits after operation. Twenty-seven patients had transient (< 20 min) or prolonged (more than 4 h) increases in amplitude (> 10%) or decreases in amplitude of less than 50% during surgery without postoperative neurological abnormalities. When the amplitude of the ASCP decreased by up to 30% with distraction force on the spine, it returned to the control value within 20 min without reduction of the distraction force.

Table 4 Relationships between changes in the ASCP and postoperative neurological findings in patients with scoliosis. †A patient in whom displacement of the extradural electrode was noticed at the end of operation is also included. ‡Partial recovery

ASCP (C1 component) changes	*n*	Duration of changes in ASCP			Postoperative neurological findings	
		Transient (< 20 min)	Prolonged (< 2–4 h)	No recovery	No change	Disturbed
No change	81				81	0
Amplitude increase > 10% (mean 17 (SEM 3)%)	13	4	0	9	13	0
Amplitude decrease < 50% (42 (7)%)	14	11	3	0	14	0
Amplitude decreases > 50% (64 (7)%) (range 58–67%)						
Without latency increase	12	8	1	3†	10	2
With latency increase > 0.2 ms	4	3	0	1	3	1
Latency increase only > 0.2 ms (0.34 (0.05) ms) (0.25–0.50 ms)	4	0	4	0	4	0
Abolishment	6	4	1‡	1	4	2
Total	134				129	5

Table 5 Relationship between changes in the ASCP and postoperative neurological sequelae in five patients

Patient No.	Age (yr)	Sex	Instrument	Latency increase (ms)	Amplitude decrease (%)	Neurological deficit
1	17	M	Harrington	0.05	57	Temporary (3 days) motor weakness
2	12	M	Harrington	0.15	53	Temporary (3 days) motor weakness and dysaesthesia
3	16	F	Harrington	0.5	58	Temporary (7 days) motor weakness and dysaesthesia
4	14	M	Harrington	Abolishment	100	Paraplegia (not recovered)
5	14	M	Zielke	Abolishment	100	Monoplegia (recovered over 3 months)

Postoperative neurological sequelae occurred in five patients who showed decreases in amplitude of more than 50% or complete abolishment of the ASCP during surgery (table 5). All these postoperative neurological sequelae occurred in the initial 80 patients in whom the distraction forces on the spine were neither rapidly nor quantitatively controlled, except for one patient in the latter 54 patients (patient No. 5 in table 5) in whom the spinal cord was injured accidentally by a hook.

There were no postoperative neurological abnormalities in the last 54 patients in whom the distraction forces were controlled by observation of the amplitudes of the ASCP, based on our criteria.

Discussion

The present study has confirmed that the ascending conducted SCP (ASCP) recorded from the posterior extradural space in response to cauda equina stimulation consists basically of three spike-like components (C1, C2, C3), followed sometimes by slower components, as reported previously [13]. The fact that the ASCP did not show any significant changes in 81 patients for several hours during the course of surgical manipulations may indicate the stability of the potentials and the minimal influence of anaesthetics and surgery. The ASCP are largely unaffected by anaesthetic agents [7, 9, 20] in doses used for surgery, which was also confirmed in the present study.

The present study has shown that patients in whom the amplitude of the ASCP exceeded 50% of the control values did not develop postoperative neurological changes, even when the distraction forces were not reduced (table 4). These results suggest that the critical level of amplitude reduction of the ASCP should be set at approximately 50% of the control value. We have also demonstrated that prolongation of latency of the ASCP, even by more than 0.2 ms, was not associated with postoperative neurological dysfunction when there were no changes in amplitude (table 4), but produced transient neurological sequelae in one of four patients when the amplitudes were reduced concomitantly to less than 50% of control values (table 4).

The present study also demonstrated that there were no postoperative neurological abnormalities in patients in whom the distraction forces could be controlled by observation of the amplitudes of the ASCP during spinal manipulations, even when the ASCP decreased in amplitude by more than 50%, as demonstrated in the last 54 patients (table 1), except for one patient (patient No. 5, table 5). However, it is possible that other factors such as differences in surgeon or technique may also have accounted for the trend in decreased incidence of neurological deficits after operation.

The critical level of amplitude reduction reported by Imai [21] and Murakami and colleagues [22] in "descending ASCP", in which extradural stimulation of the rostral spinal cord and subdural recording of spinal cord potentials were performed, was similar to our data. Similar values were reported also by Macon and colleagues [7]. However, these reported critical values are difficult to interpret, as the time course of changes, control of the distraction forces in the event of ASCP changes and several other factors such as age, body temperature or anaesthetic methods were not clearly described. Waller and colleagues [23] and Forbes and colleagues [24] have also demonstrated that amplitude reduction exceeding 50% may be associated with neurological deficits after operation in spite of release of the distraction force. Although the time to the release of the distraction force was not described, their results conflict with ours, possibly because releasing times may have differed between their study and ours.

Several methods of monitoring spinal cord function at the early and reversible stage have been developed [25]. Several groups [26–29] have described the use of scalp recordings of somatosensory evoked potentials (SEP) to monitor spinal cord function during scoliosis surgery. Anaesthetic agents, however, have variable effects on the SEP recorded from the scalp [2–5, 30], rendering this technique less useful.

Afferent spinal volleys can be recorded in the extradural space also by transcutaneous electrical stimulation of a peripheral nerve [11, 16]. Jones and colleagues [31] have also described cervical extradural recording of the ASCP evoked by peripheral nerve (a large nerve trunk in the leg) stimulation to monitor spinal cord function during Harrington rod instrumentation. Methods of peripheral nerve stimulation and extradural recording at the rostral spinal level, however, may have some disadvantages. The

amplitude of the ASCP evoked by peripheral nerve stimulation is smaller than that of the SCP evoked by cauda equina stimulation [18, 19]. Furthermore, the ASCP evoked by peripheral nerve stimulation reflects not only spinal cord function, but also peripheral nerve activity.

The advantages of monitoring spinal cord function by ASCP, as used in the present study, are: (1) high reproducibility and stability of the potentials [13], (2) safety [11], (3) simplicity of the method [11, 16, 18, 19], and (4) relatively large amplitude with minimal effect of anaesthetics on the potentials. Furthermore, the ASCP evoked by extradural stimulation of the cauda equina reflects the afferent volley conducted through the spinal cord, whereas the conducted SCP evoked by spinal cord stimulation may reflect both orthodromic and antidromic volleys, making it difficult to differentiate if each component of the potential originates from afferent or efferent volleys [13, 17, 32]. Lastly, the greatest advantage of the present method is that the distraction force can be controlled periodically during surgery by monitoring changes in ASCP.

In our 134 cases in whom ASCP were monitored, postoperative neurological deterioration was observed in only five patients in spite of a variety of changes in the ASCP (table 4). A reduction in amplitude of greater than 50% or latency prolongation of greater than 0.2 ms, or both, were noted during surgery in 20 patients (table 4) in which slight transient neurological deficits such as muscle weakness or dysaesthesia, or both, were observed in three patients. The other 17 patients developed no significant postoperative neurological deficits in terms of clinical testing. Transient (or prolonged) and permanent disappearances in potentials were observed in five and one patient, respectively, but severe neurological disturbances developed in only two patients (table 4). These results indicate that ASCP are highly sensitive to compression damage of the spinal cord caused by distraction forces on the spine.

Spinal cord dysfunction, as reflected by amplitude decreases and latency increases of the ASCP, may develop by two mechanisms: local ischaemia and mechanical injury. Amplitude decreases of less than 30% and latency increases of less than 0.2 ms by the distraction force recovered within 20 min even without reduction in force. This may indicate that amplitude decreases of less than 30% are caused by transient local circulatory disturbances, and recovery occurs by compensatory recirculation. Rapid recovery of potentials, which decreased by more than 50%, after reduction of the distraction force applied on the spine suggests that the changes in amplitude or latency of ASCP during distraction forces are caused primarily by ischaemia of the cord rather than by mechanical damage of cord tissues. However, ischaemia and mechanical injury may develop in patients in whom the ASCP show decreases in amplitude of more than 50% without recovery. Permanent abolishment of the potentials may indicate additional mechanical injury to the cord.

Another important result in the present study was that there were no false negative findings, that is there were no patients who developed postoperative neurological sequelae without changes in the ASCP during surgery. False negative results were reported in a few patients with scalp recorded SEP monitoring [29] and intrathecally recorded ASCP [22], but not in patients monitored by extradurally recorded ASCP [23, 32]. The incidence of false negative results in the literature may be related to lack of monitoring of both latency and amplitude, and other factors [33].

One possible problem with our method is that the position of the extradural catheter electrodes may be displaced by operative manipulations if the electrodes are situated close to the surgical area. Recording and stimulating electrodes should be placed as far as possible from the level of manipulation. With the monitoring methods of Kurokawa [32] and Tamaki and colleagues [9], recording and stimulating electrodes are placed in the extradural space through the operative area during surgery, but this may lead to displacement of the electrodes in the extradural space by operative manipulations.

Another problem with our method may be that the potentials we record reflect somatosensory and not motor functions of the spinal cord. However, our results suggest that parallel changes occur along sensory and motor tracts in the spinal cord during gross mechanical pressure produced by distraction forces on the spine.

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