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Motor evoked potential monitoring during spinal surgery: responses of distal limb muscles to transcranial cortical stimulation with pulse trains

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Abstract

During spinal surgery, motor evoked potentials (MEPs) were recorded from distal upper and lower limb muscles following multi-pulse transcranial electrical stimulation of the cortex. Twenty-two patients, 9 of them myelopathic, were anaesthetised with propofol ± nitrous oxide. Using trains of 3–6 pulses separated by 2 ms, consistent responses generally measuring more than 100 μV were obtained from every patient except one, and persisted with nitrous oxide concentrations as high as 74%. Responses could usually be elicited from 3 or more limbs simultaneously, although the location of the stimulating anode was sometimes critical. The lower limb responses of one patient disappeared transiently during excision of an intramedullary tumour; his leg weakness was increased for a few days after surgery. Three other patients experienced increased weakness or spasticity, two without concomitant MEP changes and one with no recordable responses. Although other methods may be preferable in some circumstances, we believe this represents an advance over previously reported non-invasive techniques for peroperative MEP monitoring, and may be particularly useful for monitoring patients with myelopathy in the thoracic region.

Keywords: Motor evoked potentials; Transcranial cortical stimulation; Peroperative monitoring; Spinal surgery; Propofol anaesthesia

1. Introduction

Patients undergoing spinal surgery are frequently at risk of potentially severe neurological complications due to compromise of the spinal cord. Techniques for monitoring the function of the sensory tracts using somatosensory evoked potentials (SEPs) are well established, and are believed to be effective in detecting the majority of problems which occur during surgery for scoliosis (e.g. Nash et al., 1977; Tamaki et al., 1984; Forbes et al., 1991). However, there are isolated reports (e.g. Lesser et al., 1986) of 'false negative' results, that is to say patients who develop a cord deficit in spite of peroperatively unchanged SEPs. The results of a large multi-centre survey (Nuwer et al., 1995) suggest that, while SEP monitoring may be effective in reducing the incidence of complications, many still occur which are not reflected by peroperative SEP changes. While some of these may be due to technical inexperience of the monitoring staff or damage to sensory tracts outside the segments monitored by the SEPs, others could reflect partial cord lesions causing mainly motor impairment and sparing the sensory pathways. The limitations of the 'wake-up' test (Vauzelle et al., 1973) as a means of ensuring motor pathway integrity are clear, and so there is considerable interest in developing electrophysiological methods for monitoring the motor tracts of the cord.

When electrodes can be located in the spinal epidural space, it is possible to stimulate the cord above the levels at risk and record the descending volley from more caudal segments (Tamaki et al., 1984). This does not assess the motor tracts exclusively, since a large proportion of the activity is likely to be due to antidromically conducted sensory potentials. A stimulator capable of safely activating the human motor cortex transcranially was first developed by Merton et al. (1982). This applies brief (50 μs) impulses of high voltage to the scalp, resulting in direct stimulation of the pyramidal cells. It has been applied to peroperative monitoring by Boyd et al. (1986), Inghilleri et

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al. (1989), Zentner (1991) and Burke et al. (1992), who recorded descending volleys from the epidural space, and Zentner (1989), Jellinek et al. (1991a) and Tabaraud et al. (1993) who recorded myogenic MEPs. The much greater difficulty of obtaining the latter in patients anaesthetised for surgery is attributable to the fact that the subjects are unable to facilitate their responses by voluntary contraction of the target muscles, and cortical excitability is itself depressed by many anaesthetic agents, particularly the halogenated gases. Jellinek et al. (1991b) were able to record responses in patients under propofol anaesthesia supplemented with nitrous oxide, but amplitudes were often very small (ca. 10 μV) and latencies were significantly prolonged by nitrous oxide concentrations greater than 20%.

In order to try to improve the practical consistency of peroperative MEP recordings, we extended the method of double pulse stimulation which enhances the responses of conscious subjects when delivered transcranially (Inghilleri et al., 1990) and of anaesthetised subjects when delivered directly to the spinal cord (Taylor et al., 1994a) to the use of short trains of impulses as described by Pechstein et al. (1994) and Deletis et al. (1995). The present account describes preliminary experience with a transcranial stimulator capable of delivering trains of up to nine high voltage shocks with an inter-pulse interval (IPI) of 0–10 ms, in order to establish the optimal stimulus parameters for peroperative monitoring.

2. Patients and methods

The subject group comprised 22 patients (15 male, 7 female, aged 23–76 years) undergoing elective spinal surgery for various complaints (Table 1). Patients with a history of epilepsy or other cerebral disease, skull fracture, craniotomy or a cardiac pacemaker were excluded. The level of surgery was cervical in 7, thoracic in 5 and lumbo-sacral in 10. Clinical evidence of myelopathy was present in 9 cases. The study was approved by the local ethical committee and the patients gave their informed consent.

In 7 patients a total intravenous anaesthetic technique was employed, using infused propofol (2,6-diisopropylphenol; Diprivan, Zeneca Ltd., Macclesfield, Cheshire, UK) supplemented with alfentanil and/or midazolam. In the remaining 15 patients, propofol was supplemented with alfentanil and nitrous oxide in concentrations of up to 74%. The patients were initially paralysed with a single bolus of atracurium besylate to facilitate tracheal intubation. No further relaxants were given. Neuromuscular block was assessed using a peripheral nerve stimulator (Bard Critical Care 750 Digital, Bard Biomedical, Westmont, IL, USA). Anaesthesia was induced with propofol 2 mg/kg and maintained with propofol at 6–10 mg/kg per h and alfentanil. The patients' lungs were ventilated with oxygen and nitrous oxide. Other parameters recorded included the blood pressure, end tidal carbon dioxide and temperature. End tidal carbon dioxide was maintained at 3.8–4.2 kPa and body temperature was kept at 37°C with a warm air mattress.

Transcranial electrical stimulation was applied using a prototype Digitimer D185 stimulator (Digitimer Ltd, Welwyn Garden City, Hertfordshire, UK). Nine-millimetre silver/silver chloride EEG cups were attached to the scalp with collodion and the contact resistance reduced to below 5 kΩ by scarification. The electrodes were located over the hand and foot areas of the motor cortex, approximately 2 cm anterior to locations C3, C4 and Cz (International 10–20 system for the placement of EEG electrodes). The anode was usually at the midline electrode, anterior to Cz, and the cathode at one of the lateral locations, but other combinations were tried in every case. Trains of 1–6 stimuli 50 μs in duration were delivered with a voltage range of 300–1000 V and an inter-pulse interval (IPI) of 1–6 ms. At least 1 min was allowed to elapse between each stimulus train. The total number of shocks delivered to the brain was recorded in every case.

For MEP recording, pairs of uninsulated stainless steel needle electrodes were inserted about 1 cm apart in the abductor digit minimi (ADM) and abductor hallucis (AH) muscles on one or both sides. Both upper and lower limb MEPs were recorded simultaneously in every case except 4; in patients undergoing surgery below the cervical region the responses of one upper limb were recorded in addition to lower limb MEPs in order to control for systemic factors which might affect cortical excitability. Recordings were obtained on the 4 channels of a Nihon-Kohden Neuropack 4 Mini evoked potential recorder (Nihon-Kohden Europe Ltd., Brentford, Middlesex, UK), using a timebase of 100 ms, a gain of 50–200 μV/cm and a bandpass of 20–3000 Hz. All recordings were stored on disc for analysis. Pre- and postoperative recordings were not made on account of the much greater discomfort associated with multi-pulse as compared with single pulse or magnetic stimulation.

3. Results

A mean of 135 transcranial shocks (range 12–481) was given to each subject in trains of 1–6. The mean duration of monitoring was 95 min (range 15–250 min). The only medical complication associated with the stimulus was a bitten tongue in one patient who with each pulse train exhibited a heavy twitch of the neck and trunk in addition to the limb muscles. There were no postoperative sequelae attributable to the stimulus, and no burn marks were observed at the stimulation sites.

The minimum number of pulses required to produce an MEP was assessed, starting with single and double pulses in 12 patients. After full recovery from neuromuscular block, responses to single pulses were consistently recorded in only 3 subjects, none of whom received nitrous oxide. In view of the findings of Inghilleri et al. (1990)

Table 1
Patient data, clinical, anaesthetic and surgical details

	Age (years)	Sex	Level	Procedure	Preop myelopathy	N_2O
1	68	M	L	Laminectomy for degenerative disease	–	–
2	60	F	L	Microdiscectomy	–	Y
3	34	F	C	Anterior discectomy and fusion	–	–
4	30	F	L	Microdiscectomy	–	–
5	34	F	L	Laminectomy for degenerative disease	–	–
6	71	M	L	Laminectomy for degenerative disease	–	–
7	23	M	T	Laminectomy for cavernoma excision	Y	–
8	76	M	T	Laminectomy for arteriovenous malformation	Y	–
9	75	M	C	Anterior discectomy and fusion	Y	Y
10	25	F	L	Laminectomy for schwannoma excision	–	Y
11	56	M	C	Laminoplasty for intramedullary tumour excision	Y	Y
12	35	M	L	Microdiscectomy	Y	Y
13	37	M	C	Anterior discectomy and fusion	–	Y
14	56	M	C	Anterior discectomy and fusion	–	Y
15	49	M	T	Laminectomy for intramedullary tumour excision	Y	Y
16	45	F	L	Microdiscectomy	–	Y
17	50	M	C	Anterior discectomy and fusion	–	Y
18	47	M	C	Laminoplasty for degenerative disease	Y	Y
19	40	M	L	Microdiscectomy	–	Y
20	51	F	L	Laminectomy for degenerative disease	–	Y
21	69	M	T	Laminectomy for meningioma resection	Y	Y
22	50	M	T	Costotransversectomy for kyphotic deformity	Y	Y

M, male; F, female; C, cervical; T, thoracic; L, lumbar.

using double pulse transcranial stimulation in conscious subjects, and of a pilot study performed by ourselves on one normal volunteer, the responses to trains of two or more transcranial shocks were initially assessed with an IPI of 2 ms. Responses to double pulses were obtained in 7 patients (two of whom received nitrous oxide); in two cases these were of very low amplitude even at the maximum output of 1000 V. Using longer trains of stimuli, consistent responses were obtained in 21/22 patients. The number of pulses necessary to produce a 'maximal' response (identification of which was somewhat uncertain on account of the high inter-response variability) ranged from two in two cases to 6 in one case, most subjects requiring 4 or 5 pulses (Table 2). Beyond this train length, further pulses tended to prolong the duration of the MEP, rather than increase its amplitude (Fig. 1).

The effect of varying the inter-pulse interval was studied in 4 cases; maximal or near-maximal responses were recorded with inter-pulse intervals of 1–3 ms and a progressive degradation was noted with longer IPIs (Fig. 2).

The voltage necessary to produce a maximal response ranged from 300 to 900 V (Fig. 3). When the length of the train producing a maximal response at the lowest voltage was reduced by one pulse, even a very large increase in the voltage of the stimulus was not usually effective in restoring the response. For example, in patient number 20 single and double pulses of 1000 V produced no response, triple pulses of 1000 V produced a clearly submaximal response, yet maximal responses to quadruple pulses were recorded with an intensity of only 500 V.

The intersubject variability of MEP amplitude was extremely wide (25–1600 μV for the upper limbs, 15–300 μV for the lower limbs) and the range of latencies also quite wide (upper limbs 18–31 ms, lower limbs 35–55 ms). Within each subject the MEP amplitudes were also rather variable, sometimes fluctuating by 50% or more between consecutive responses (Fig. 4). Latencies were much more constant but sometimes exhibited quantum variation in units of the IPI; for the subject illustrated in Fig. 5 it appears that the MEP was sometimes elicited by the fourth and sometimes the third pulse in the train.

The location of the stimulating anode and cathode was usually not critical. In every case except one MEPs were recorded simultaneously from at least two (usually 3) limbs with the same montage of stimulating electrodes. MEPs could usually be elicited from both lower limbs with the anode at the midline location, and from both contralateral limbs with the anode over the lateral cortex. Sometimes the anode and cathode could be reversed without affecting the responses greatly, but on other occasions the optimal electrode configuration was more critical and unpredictable. For example, in patient number 20 anodic stimulation at the midline activated only one lower limb, as did anodic stimulation at the right pre-central location, but with the anode on the left and the cathode on the right near-maximal responses were simultaneously evoked from all 3 monitored limbs (Fig. 5).

The effect of anaesthetic agents was not studied formally. No nitrous oxide was given in 7 cases, while in the remaining 15 the maximum concentration ranged

Table 2

MEP data from upper (UL) and lower (LL) limbs

Case	Limbs monitored	Responses absent	Total pulses	Duration (min)	Response to pulse		Required for maximal MEP		Maximal UL response		Maximal LL response	
					Single	Double	Pulses	Volts	Latency (ms)	Amplitude (μV)	Latency (ms)	Amplitude (μV)
1	2 × UL	1 × UL	178	50	Nil	Present	2	300	24.2	1600	–	–
2	2 × LL	–	481	60	Nil	Nil	5	700	–	–	44.2	150
3	2 × UL 2 × LL	–	12	15	Present	Present	2	600	18	600	35	300
4	1 × UL 2 × LL	–	172	60	Nil	Minimal	4	700	20.2	150	36.1	250
5	1 × UL 2 × LL	–	165	120	Present	Present	3	600	19	200	35	150
6	2 × UL 2 × LL	–	90	60	Present	Present	3	400	21	800	44.8	300
7	1 × UL 2 × LL	–	66	60	Nil	Nil	4	900	24.5	50	49	30
8	1 × UL 2 × LL	–	185	110	Nil	Nil	4	900	26	100	49.2	15
9	1 × UL 1 × LL	1 × LL	90	210	Nil	Nil	4	800	31.1	50	–	0
10	1 × UL 2 × LL	–	81	75	Nil	Minimal	3	800	27	200	40.2	300
11	2 × UL 2 × LL	1 × UL	216	100	–	–	5	600	25.4	1440	50	186
12	1 × UL 2 × LL	–	44	30	–	–	5	550	30.4	400	50.3	50
13	2 × UL 2 × LL	1 × LL	48	130	–	–	4	550	25.4	300	40	230
14	2 × UL 1 × LL	2 × UL	66	100	–	–	6	600	–	0	55.4	300
15	1 × UL 2 × LL	1 × LL	162	250	–	–	5	600	22.8	800	51.4	36
16	1 × UL 2 × LL	–	40	40	–	–	5	500	23.8	100	45.6	95
17	2 × UL 2 × LL	1 × UL	76	120	–	–	5	600	32	25	55	40
18	2 × UL 2 × LL	–	80	90	–	–	5	550	28.5	200	48	80
19	1 × UL 2 × LL	–	145	150	Nil	Present	3	550	20.6	80	37.6	200
20	1 × UL 2 × LL	–	120	45	Nil	Nil	4	500	23.6	500	42.8	145
21	2 × LL	–	400	240	–	–	4	600	–	–	48.2	158
22	2 × LL	2 × LL	60	60	–	–	–	–	–	–	–	0

from 50% to 74%. On no occasion was any MEP deterioration associated with increasing nitrous oxide concentration, although mean MEP amplitudes were somewhat lower in the patients who received nitrous oxide (370 μV compared with 500 μV for upper limb responses, 130 μV compared with 174 μV for the lower limbs) and mean latencies were markedly longer (26.4 compared with 21.8 ms for the upper limbs, 46.8 compared with 41.5 ms for the lower limbs). The mean number of pulses needed to evoke a maximal response was 3.1 in the total intravenous cases, 4.4 in the patients who also received nitrous oxide, but the mean voltage employed was similar in the two groups (630 V compared with 610 V). In 3 cases the introduction of isoflurane in moderate concentrations had a markedly deleterious effect. The effect of the muscle relaxant (a single bolus of atracurium besylate) was very profound; in most instances no response could be recorded for 30–45 min, occasionally for almost 1 h, and further enlargement of the MEPs was sometimes noted even after the peripheral nerve stimulator suggested full recovery from neuromuscular block.

In the group as a whole, responses were recorded perioperatively from 57/67 monitored limbs, including at least one 'at risk' limb in every case except one. The 10 limbs from which no MEP could be recorded derived from 8 patients, 5 of whom had myelopathy at a level which could account for the absent responses. The one patient (number 22) in whom no responses could be recorded had

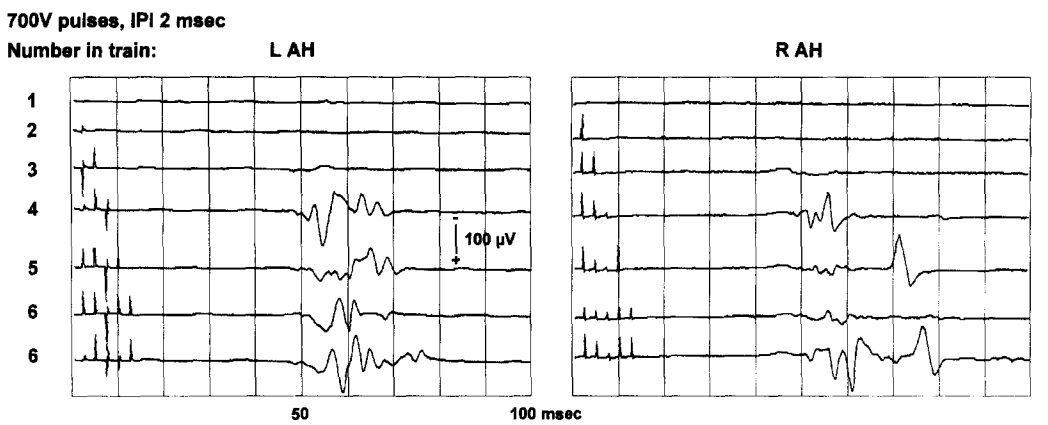

Fig. 1. Patient number 2, responses of left and right AH, effect of increasing the number of pulses in the train. MEPs are virtually absent with trains of 1–3 pulses, and of similar amplitude (although variable morphology and increasing duration) with trains of 4–6 pulses.

a severe kyphotic deformity of the thoracic spine causing marked spasticity and sensory impairment. In one patient without neurological impairment no MEP could be recorded from the left upper limb, but this may have been because no stimulating electrode was attached at the right lateral scalp location. In two other non-myelopathic cases, absent or inconsistently elicited responses from one limb out of 4 may have been because the optimal montage of stimulating electrodes was not discovered.

Symptoms and signs of myelopathy were present prior to the commencement of surgery in 9 cases, in 5 at thoracic and 4 at cervical level. MEPs were recorded peroperatively from both lower limbs in 3/5 patients with thoracic myelopathy, absent on one side in one and absent on both sides in one patient. Of the 4 patients with cervical myelopathy, lower limb responses were present bilaterally in two, present unilaterally in one (the other side not monitored) and absent unilaterally in one (the other side not monitored); upper limb MEPs were present bilaterally in one, present unilaterally in one (the other side not monitored), absent bilaterally in one and absent unilaterally in one. In every case except one, MEPs were recorded from at least one limb affected by myelopathy. In comparison with 12 non-myelopathic patients, the mean amplitude of lower limb MEPs was lower (89 compared with 184 μV) and the mean latency longer (50.1 compared with 42.2 ms) in the 9 myelopathic patients. This result may have been slightly influenced by the fact that a greater proportion of the myelopathic cases were anaesthetised with nitrous oxide in addition to propofol.

On account of the marked amplitude variability between consecutively recorded MEPs, it was not possible to establish a reliable criterion for significant deterioration in this

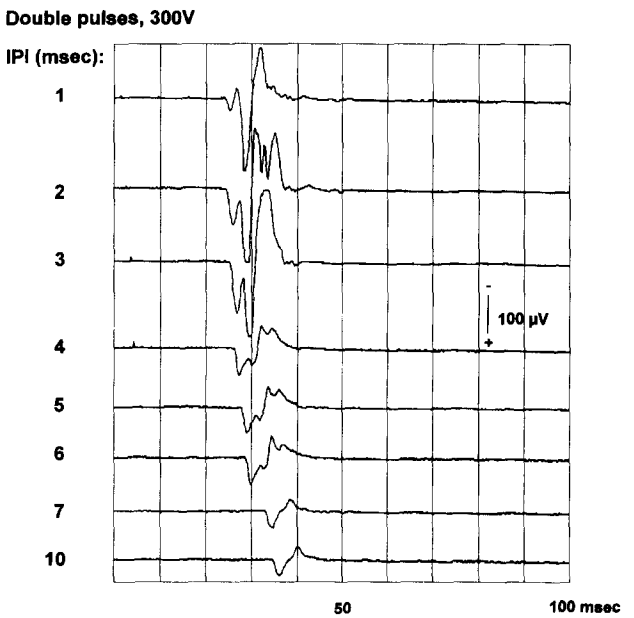

Fig. 2. Patient number 1, responses of left ADM, effect of increasing the inter-pulse interval with double pulse stimulation. MEP amplitude is largest with an IPI of 2 or 3 ms. The increasing latency is closely related to the IPI, except between 6 and 7 ms where the large latency increase is due to the failure of one motor unit to respond at the longer interval.

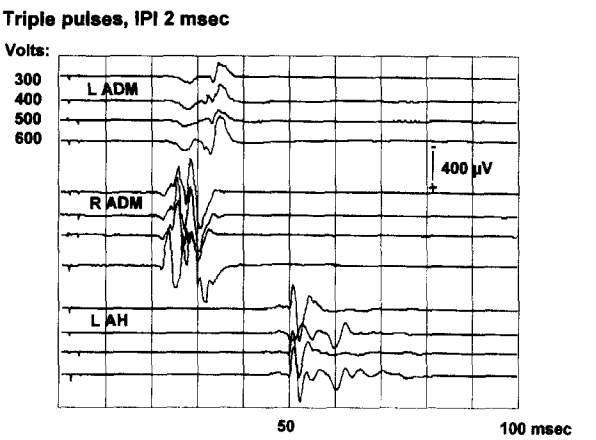

Fig. 3. Patient number 6, responses of both upper and one lower limb showing minimal effect of increasing stimulus voltage with triple pulses. With stimulating electrodes at the midline (anode) and over the left central area (cathode), only very small responses were recorded from right AH (not shown).

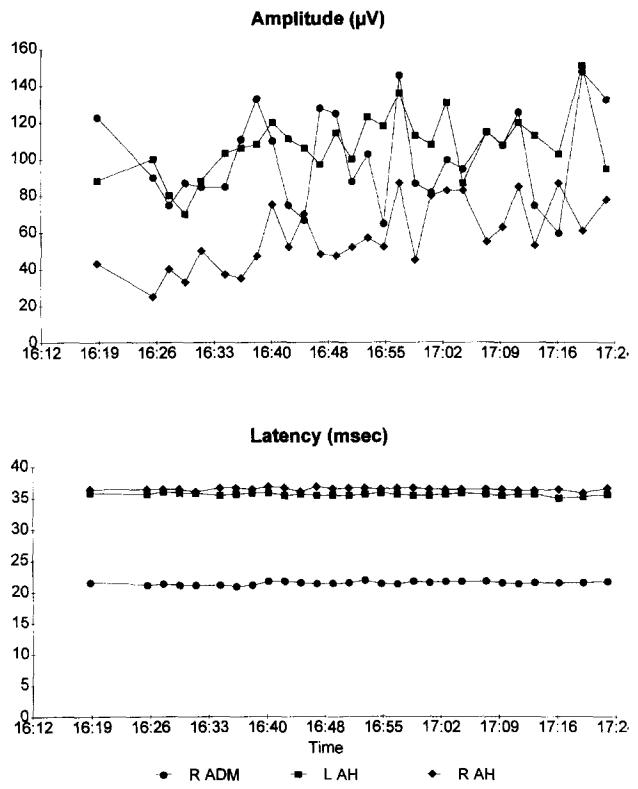

Fig. 4. Patient number 5 (triple pulses, IPI 2 ms, 600 V) showing marked variability of MEP amplitude but consistency of latency.

small group of patients. Nevertheless, the MEPs were reviewed in relation to postoperative neurological deterioration which occurred in 4 patients. In patient number 15 MEPs were transiently lost during resection of a thoracic ependymoma. No responses could be recorded at any time from left AH and the initially small responses from right AH disappeared for about 30 min before making a full recovery. The resection was terminated when the MEPs were lost, but the patient awoke with a worsened paraparesis which improved to the preoperative level over a few weeks. In patient number 7 a transient increase in MEP amplitude from left AH was noted during the resection of a thoracic cavernous malformation, responses of consistently less than 30 μV increasing briefly to more than 200 μV before returning rapidly to the baseline level. Postoperatively this patient developed worsened symptoms of a right-sided myelopathy and a worsened pain syndrome; the MEP change was therefore probably coincidental. Patient number 8 had MEPs of low amplitude which remained unchanged during resection of a thoracic arteriovenous malformation. A slight increase in spasticity was noted in later follow-up although not immediately after surgery, perhaps on account of its eclipse by more severe systemic complications. Finally, patient number 22 in whom no MEPs could be recorded experienced a worsening of lower limb weakness after costotransversectomy to stabilise a severe kyphotic deformity.

4. Discussion

The findings in a small group of patients suggest that peroperative monitoring of MEPs to trains of transcranial electrical stimuli is a practical technique, compatible with a standard anaesthetic regime. Monitoring of one or more endangered limbs was possible in 21/22 cases, 9 of whom had pre-existing myelopathy. Although much smaller than in conscious subjects, the MEP amplitudes were generally larger and the voltage required to produce a 'maximal' response usually lower than with peroperative transcranial stimulation with single pulses (Jellinek et al., 1991a; Tabaraud et al., 1993). Comparison with preoperative recordings was not done, mainly because it would be difficult to compare the responses obtained with different forms of stimulation under very different anaesthetic conditions, but might be useful to screen for those patients with too severe myelopathy for MEPs to be usefully monitored.

It is generally found (e.g. Haghighi et al., 1990) that anaesthesia with volatile halogenated agents has too profound an effect on MEPs to single transcranial pulses to be compatible with peroperative monitoring. Zentner and

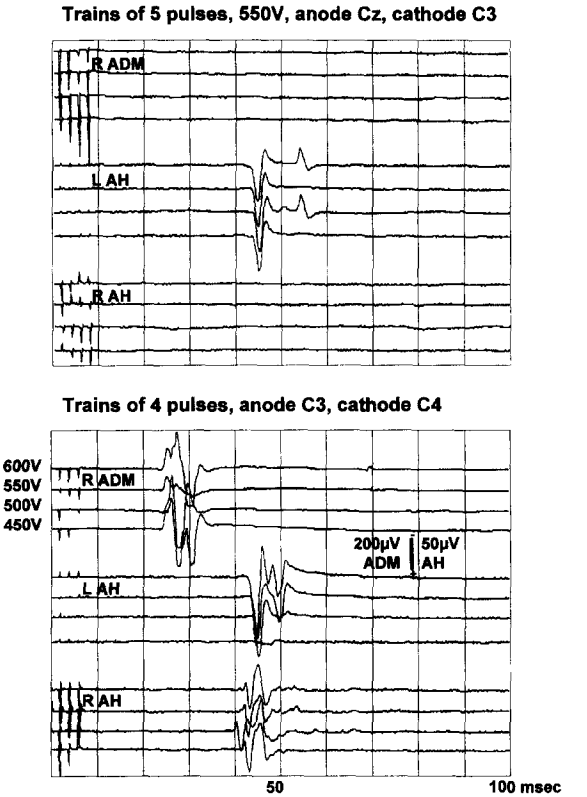

Fig. 5. Patient number 20, effect of anode and cathode location. Anodic stimulation just anterior to Cz elicits responses only from the left lower limb. With the anode anterior to C3 responses are elicited from the right upper and lower limbs as well as the left lower limb, requiring only trains of 4 × 500 V stimuli for maximal amplitude. Note the tendency for the right AH responses to fluctuate in latency by about 2 ms between consecutive sweeps.

Ebner (1989) and Zentner et al. (1989) also reported a suppressive effect of nitrous oxide on MEPs to single pulse transcranial electrical stimulation, prompting the use of neuroleptanaesthesia (Zentner, 1989). Jellinek et al. (1991b), on the other hand, found the responses to single pulses to be recordable, albeit with reduced amplitude and prolonged latency, under Propofol anaesthesia with nitrous oxide concentrations of up to 50%. We did not study the effect of nitrous oxide systematically, but found that with multi-pulse stimulation monitoring was possible with concentrations as high as 74%. For MEP monitoring to become standard, it is clearly advantageous for the anaesthetic technique to conform to accepted practice. Some anaesthetists are concerned about the possibility of awareness which has been reported in a patient receiving total intravenous anaesthesia without nitrous oxide (Sandrin and Nordstrom, 1993).

In the present series no muscle relaxants were infused, and it might take as long as 1 h for the responses to appear after a single post-induction bolus; a potential disadvantage, therefore, is that MEP monitoring by this technique may be unfeasible during very short procedures. One possible solution may be to use a shorter acting muscle relaxant such as mivacurium. The very high trial-by-trial variability of MEP amplitude makes it difficult to define criteria for a minor degree of deterioration as distinct from a complete loss of the response; at present, therefore, the test must be considered a qualitative rather than a quantitative one. It is uncertain whether the method may be applied safely in patients with a cardiac pacemaker, a history of epilepsy or other cerebral disease, and in those undergoing craniotomy or surgery in the high cervical region it is possible that the paths of current flow may differ from those usually followed and could be shunted by instruments in contact with moist tissue. A final disadvantage is that the muscle twitch produced by transcranial stimulation is often generalised, such that the surgeon may need to be informed every time a stimulus is to be delivered. However, the only complication attributable to the stimulus was a bitten tongue in a patient whose proximal muscle twitches were particularly violent. Bite blocks should therefore be used.

In a brief account, Rodi et al. (1996) compared the responses in muscle and the epidural space to trains of 1–5 transcranial pulses separated by 2 ms. Whereas single or double stimuli elicited only D-waves in the corticospinal tract, and no peripheral responses, trains of 3 or 4 pulses evoked the appropriate number of D-waves and also multiple I-waves, with the result that muscle responses were also produced. It appears, therefore, that multiple corticospinal volleys separated by about 2 ms are necessary in order for the lower motor neurone to be fully depolarised, and that the excitability of the motor cortex in anaesthetised patients can also be enhanced by the use of stimulus trains. In abstract, the same group of authors (Deletis et al., 1995) evaluated the technique in 44 patients undergoing surgery of the spine or brain, reporting that a pulse width of 500 μs was more effective than stimuli of shorter duration. While no complications were reported, our own view is that greater caution may be desirable when applying relatively long-duration shocks to the brain.

Some exacerbation of weakness and/or spasticity occurred in 4 patients; in only one of these did the MEPs disappear for a time during the procedure, although the absence of any response from the start of surgery in one of these might have indicated that some impairment had already occurred. Considerably more experience is needed before it can be established what degree of intraoperative MEP deterioration should be regarded as pathologically significant. However, various hypotheses may be invoked to account for the failure of the technique to detect clinical deterioration in two cases. (1) Sampling effect. Minor damage to the corticospinal tracts may affect only a small number of fibres, possibly not including those which innervate abductor hallucis or abductor digiti minimi (these muscles were selected largely on account of their ease of access). A better correlation between MEP loss and significant clinical weakness might be achieved by monitoring more proximal muscles such as tibialis anterior, in which a partial loss of power is more likely to be of significance to the patient. (2) Innervation of lower motor neurones by multiple corticospinal axons. Since motor units respond in 'all or nothing' fashion, and relatively few were sampled particularly in abductor hallucis (sometimes only one), it is possible that a response may still be elicited when some of the innervating axons are rendered dysfunctional. A more quantitative estimate of motor tract integrity might be achieved by use of surface electrodes, sampling a larger proportion of active units. (3) A lesion sparing the corticospinal but affecting, for example, the dorsal reticulospinal tract might cause increased spasticity without weakness, and without affecting the MEPs.

It is pertinent here to consider other methods which have been used for peroperative MEP monitoring, firstly those in which peripheral responses were recorded to direct stimulation of the cord. The 'neurogenic motor evoked potentials' recorded from peripheral nerves to non-invasive cord stimulation (Owen et al., 1990) are open to question owing to the likelihood of a substantial contribution from antidromically conducting sensory fibres. Methods for stimulating the spinal cord using single or double pulses via epidural electrodes (e.g. Taylor et al., 1994a), transcutaneous needles and oesophageal electrodes are useful in scoliosis surgery, especially when an epidural electrode is already in place for SEP recordings, but are inapplicable during surgery in the high cervical region; they are potentially open to the criticism that when the corticospinal tracts are damaged a motor response may be mediated by antidromic conduction in sensory fibres of the dorsal columns (Poncelet et al., 1995), although this has not been proven to occur in humans.

Several other groups have recorded corticospinal tract potentials from the epidural space to transcranial stimulation. The method developed by Levy (1987) involved transcranial stimulation with relatively low (<80 mA) stimulus currents through scalp (anode) and palatal (cathode) electrodes; although it was possible to record descending neurogenic potentials from both the epidural space and the periphery, these often required long periods of averaging. Corticospinal tract potentials can be recorded from the epidural space to single high-voltage transcranial impulses (Boyd et al., 1986; Inghilleri et al., 1989; Burke et al., 1992). While this method possesses the advantage of compatibility with muscle relaxants, it is uncertain whether the small potentials recorded in the lower thoracic region will be consistently identifiable without averaging in adult patients with and without myelopathy. Compared with these techniques, the monitoring of myogenic MEPs has the additional advantage that the projections to the 4 limbs can be assessed separately. During surgery below the cervical region, changes in cortical excitability can be controlled for by recording MEPs from the upper as well as the lower limbs.

Rossini et al. (1985) described a method for non-invasive transcranial electrical stimulation using relatively low-voltage stimuli, delivered via a focal anode in conjunction with a band or series of plates around the head to serve as cathode. As far as we are aware, intraoperative application of this method has not been described in the literature, but its effectiveness would probably be increased by use of multiple pulses. Ugawa et al. (1991) showed that in conscious subjects myogenic MEPs can be recorded in response to single transcranial pulses delivered at the level of the cervicomedullary junction. It is probable, however, that stimulation here produces only a single corticospinal volley, which may be insufficient to depolarise the lower motor neurone in anaesthetised patients. Magnetic cortical stimulation, as first developed by Barker et al. (1985), is clearly preferable as a means of assessing central motor conduction in conscious patients, being much less painful than transcranial electrical stimulation. Although more vulnerable to anaesthetic agents on account of the fact that pyramidal cell activation only takes place via cortical interneurones, magnetically induced MEPs have been successfully recorded in anaesthetised patients to single (e.g. Edmonds et al., 1989; Schmid et al., 1992; Fraser et al., 1994; Herdmann et al., 1994; Kothbauer et al., 1994) and double pulses (Taylor et al., 1994b), but possess no inherent advantages over electrically elicited responses in this context and may present additional difficulties for the surgeon and anaesthetist owing to the size and shape of the stimulating coil. There are now machines capable of delivering trains of magnetic stimuli but the equipment is bulky and costly. Of the available methods, therefore, we feel that MEPs to multi-pulse transcranial electrical stimulation offer the best prospects for widespread application.

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