

# Relevance of intraoperative D wave in spine and spinal cord surgeries

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## Abstract

**Purpose** The combined recordings of epidural-(D wave) and muscle motor evoked potentials (m-MEPs) have been proposed in many studies in intramedullary spinal cord tumour (IMSCT) surgery, although not all agree. Furthermore, the usefulness of the intraoperative monitoring of motor systems using these methods in other types of spine surgery has not yet been clearly confirmed. The aim of this study is to test the impact of intraoperative D wave on the monitorability and motor outcome in spine surgery.

**Methods** Intraoperative recording of posterior tibial nerve somatosensory potentials, lower limb m-MEPs (LLm-MEPs) and epidurally recorded D wave caudally to the surgical level was attempted in a total of 103 spine and spinal cord surgeries (23 IMSCT, 55 extramedullary spinal cord tumours and 25 myelopathies).

**Results** There was a 97.1 %, overall monitorability where at least 1 of the 3 modalities was applicable in 100 surgical procedures. Baseline LLm-MEPs were recorded bilaterally in 85 cases and unilaterally in 11. A caudal D wave was recorded in 97 cases. Transient, or persistent intraoperative modifications occurred in 14/23 IMSCT, 5/55 extramedullary spinal cord tumours and in 2/25 myelopathies. The presence of a persistent stable caudal D wave was predictive of a good motor outcome even when the LL-MEPs were absent and/or when lost during surgery.

**Conclusions** Not only is intraoperative D wave recording to be considered mandatory in IMSCT surgery but it should also be attempted in other types of spine/spinal cord surgeries.

**Keywords** Intraoperative neurophysiology · D wave · Epidural motor evoked potentials · Muscle motor evoked potentials · Spine surgery · Spinal cord surgery

## Introduction

Persistent neurologic sequelae may be the devastating consequences of spine and spinal cord surgery. The aim of neurophysiologic intraoperative monitoring (IOM) is to identify a spinal cord injury at a reversible stage or, in the case of neurologic damage, its documentation, as well as to provide information as to motor outcome.

An ideal technique tailored to this aim should have a solid neurophysiologic basis, be system-specific, provide a (*quasi*) real-time assessment, be applicable even in compromised patients and it should be safe.

The introduction of transcranially motor evoked potentials (MEPs) represented a significant step forward for intraoperative assessment of motor pathway function in spine surgery [1–7]. Two methodologies have been developed to elicit MEPs by transcranial electrical stimulation [7]:

1. Recording the D wave directly from the epidural space (e-MEPs; in this study e-MEPs and D wave are used as synonyms) evoked by a single electrical shock (single pulse technique) [1, 2];
2. Recording of MEPs in limb muscles (m-MEPs) elicited by a short train of electrical stimuli (multipulse technique) [4, 5].

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The information provided by these two techniques is complementary, as the D wave is generated by the direct activation of the axons of fast-conducting fibres of the cortico-spinal tract [8]. Whilst m-MEPs depend also by the excitability of facilitatory cortical motor neurons, beyond the spinal cord conductivity and the excitability of lower motoneurons [7, 9].

Numerous studies have proposed the combined use of D wave recordings and m-MEPs in intramedullary spinal cord surgery [6, 10–13], however, not all literature is in agreement [14–16].

Furthermore, the usefulness of the IOM of motor systems using both methods in other types of spine surgery has still not been fully clarified. This is particularly true in compromised patients where the multipulse technique may fail to evoke m-MEPs in one, or more target muscles [3, 16]. Indeed, epidurally recorded D wave is mainly generated by the sub-anodal hemisphere, but a contribution from the contralateral cortical spinal tract is highly probable, particularly with the stimulation intensities used in spine surgery [17, 18].

The aims of this study were:

1. To investigate the registrability of the D wave caudal to the surgical site in comparison with neurologic status, posterior tibial nerve somatosensory evoked potentials (ptn-SEPs) and lower limbs muscle MEPs (LLm-MEPs)
2. To study the impact of intraoperative D wave recording on motor outcome in a series of spine and spinal cord surgical procedures.

## Materials and methods

An attempt was made to carry out LLm-MEP, e-MEPs and SEPs monitoring in a total of 103 surgical procedures for 101 patients (61 females, 40 males, average age  $56.3 \pm 19.2$  years, range 3–85). Surgery was planned for intramedullary spinal cord tumour (IMSCT) resection in 23 procedures, for extramedullary spinal cord tumours (EMSCT) in 55 and 25 for myelopathies. Three surgical procedures involved the occipito-cervical region, 36 the cervical cord, 9 the cervico-dorsal level and 55 the dorsal level.

The clinical data are summarized in Table 1.

Any patients with lesions located below D10, or who had documented desynchronized D waves during previous surgical procedures were excluded. Preoperative neurological status was scored by the McCormick scale [19] as, although this scale has been proposed for IMSCT, it can also be used for scoring neurologic status in other spinal cord pathologies (Table 2).

There was a McCormick grade of I in 30 procedures (29.13 %), II in 48 (46.6 %), III in 17 (26.5 %) and IV in 8 (7.77 %).

**Table 1** Clinical data of 103 procedures on 101 patients

	IMSCT	EMSCT	Myelopathies	Total
Patients ( <i>N</i> %)	23 (22.8)	53 (52.5)	25 (24.7)	101 (100.0)
Gender ( <i>N</i> %)				
Female	11 (52.2)	35 (66)	14 (56)	61 (60.4)
Males	12 (47.8)	18 (34)	11 (44)	40 (39.6)
Age (years)				
Average (SD, range)	$41.3 \pm 21.1$ (3–73)	$60.6 \pm 16.3$ (12–86)	$60.6 \pm 17.1$ (21–81)	$56.3 \pm 19.2$ (3–86)
Aetiology				
	Ependymoma 12	Meningioma 35	Spondylosis 12	
	Pilocytic Astrocytoma 4	Neurinoma 11	Disk herniation 4	
	Astrocytoma 3	Epidural MTX 6	SC herniation 2	
	Cavernoma 1	Other 3	AV dural fistula 2	
	Dermoid Cyst 1		Other 5	
	MTX 2			
Total	23 (22.3)	55 (53.4)	25 (24.5)	103
Level				
Occipito-cervical		1	2	3
Cervical	3	19	14	36
Cervico-dorsal	7	1	1	9
Dorsal	13	34	8	55

IMSCT intramedullary spinal cord tumours, EMSCT extramedullary spinal cord tumours, SD standard deviation, MTX metastasis, SC spinal cord, AV artero-venous

**Table 2** McCormick's clinical/functional classification scheme

Grade	Definition
I	Neurologically normal; mild focal deficit not significantly affecting function of involved limb; mild spasticity or reflex abnormality; normal gait
II	Presence of sensorimotor deficit affecting function of involved limb; mild to moderate gait difficulty; severe pain or dysesthetic syndrome impairing patient's quality of life; still functions and ambulates independently
III	More severe neurological deficit; requires cane/brace for ambulation or significant bilateral upper extremity impairment; may or may not function independently
IV	Severe deficit; requires wheelchair or cane/brace with bilateral upper extremity impairment; usually not independent

All patients gave an informed consent after having been informed that potential risks included: seizures, skin burns from stimulating electrodes, tongue/lip bites, cardiac arrhythmias, inadvertent injury caused by TES-induced patient movement, epidural bleeding and/or infections.

The anaesthetic protocol used during surgery included a combination of the two drugs, remifentanyl and propofol, with total intravenous anaesthesia (TIVA). Induction was obtained with a continuous infusion of Remifentanyl at 0.10–0.20 mg/kg/min and maintained with 0.25–0.40 mg/kg/min. Target-controlled infusion was used for Propofol with a plasma concentration for induction of 3–4 mg/ml and maintenance with 4–5 mg/ml. No muscle relaxants were used after induction and intubation.

Ptn-SEPs were elicited by a 100–300  $\mu$ s square-wave electrical pulses presented sequentially to the posterior tibial nerve at the ankle (rate 4.1–7.1/s, stimulus intensity adjusted individually from 15 to 40 mA). In order to optimize the montage, monopolar needle electrodes were placed at Cz', C3', C4' and Fz (international 10-20 EEG system) and the best traces among Cz'-Fz, C3'-Fz, C4'-Fz, C3'-C4, C4'-C3 were used for monitoring. Filtering was typically 30–1,000 Hz, with a 100 ms analysis time; averaging was stopped manually at such times as potentials were clearly reproducible.

The m-MEPs were elicited with a brief duration of transcranially applied electrical pulse anodal electrical stimulus train ( $N = 3-7$ , ISI 2–4 ms), delivered by two corkscrew-type electrodes inserted over the motor cortex regions, at C1, C2, C3 and C4 (international 10-20 EEG system). A C1–C2, or C3–C4 dipole was used to elicit right m-MEPs and vice versa. Stimuli were delivered through a commercially available constant-voltage electrical stimulator (D185; Digitimer, Welwyn Garden City, United Kingdom) (pulse width = 50  $\mu$ s, voltage 200–700 V) or a constant-voltage stimulator (CRO STIM 2, Inomed, Tenningen, Germany; pulse width = 500  $\mu$ s, current

80–200 mA). Responses were recorded on commercially available neurophysiology instrumentation (Nicolet Endeavor; Nicolet Biomedical, Madison, WI, USA). Right extremity MEPs were monitored after left-cranium anodal stimulation and vice versa.

The m-MEPs were recorded by a needle electrode placed in the muscle with a belly-tendon montage from the abductor pollicis brevis in the upper extremities and both the tibialis anterior and the abductor hallucis muscles in the lower extremities. The time base was 100–200 ms and the filter bandpass 30–3,000 Hz, occasionally a restricted bandpass was used to reduce artefacts. A rolled piece of gauze was used as a bite block after induction, to avoid lip and/or tongue bites.

Two flexible three-contact platinum epidural electrodes (CEDL-3PIDINX, Ad-Tech Medical instruments corporation, Racine, WI, USA) were inserted by the surgeon above and below the site of surgery, to record e-MEPs.

The D waves were elicited by a single anodal stimulus, delivered with the same electrodes and stimulators as that used for the m-MEPs, with a constantly lower stimulus intensity; filters were typically 200/500–3,000 Hz. The time base was 10–50 ms and, in some cases, an average of 4–10 responses was necessary to improve noise to signal ratio.

The recording montage was electrode 1 to 2 (active to reference) and/or 2 to 3 for the rostral electrode and 2 to 1 and/or 3 to 2 for the caudal electrode, so as to obtain the same polarity response from both electrodes.

A persistent unilateral, or bilateral amplitude loss of at least 50 % of cortical SEPs was used as warning criteria and the surgical team was informed to be on the alert for an amplitude of D wave decrease between 30 and 50 % of baseline values. Any decrement of D waves over and above that of 50 % of baseline value was considered significant. Because there is a large trial-to-trial variability of the normal background for m-MEPs, the warning criteria were set as the disappearing of responses. However, the surgeon was warned if there were persistent amplitude decrements of more than 60 % of baseline values, even if they were not associated to a reduction of complexity.

## Results

With the exception of one minor tongue bite, due to the bite block slipping out of place during surgery, none of aforementioned IOM complications were reported in our patients. There was an overall monitorability of 97.1 %, where at least 1 of the 3 modalities was applicable in 100 surgical procedures. Indeed, in three markedly compromised subjects (McCormick grade IV), baseline ptn-SEPs, LLm-MEPs and D wave from the lower epidural electrode were absent.

Therefore, the data herein reported refer to 100 surgical procedures, carried out in 98 subjects where it was possible to apply at least 1 intraoperative neurophysiologic technique.

Baseline ptn-SEPs were recordable for a total of 79 procedures, 74 bilaterally and 5 unilaterally. Baseline LLm-MEPs were recorded bilaterally in 85 surgical procedures and unilaterally in 11. However, whilst a clear caudal D wave was recorded in 97 subjects, it was absent in 3 who were affected by IMSCT and poorly compromised (McKormick grade I in two, II in 1). Table 3 summarizes the data.

As shown in Table 3, there was a good correlation between neurological status and monitorability of both ptn-SEPs and LLm-MEPs. Baseline bilateral ptn-SEPs were present bilaterally in 85.9 % of grades I–II and in 31.8 % of grades III–IV, unilaterally in 2.6 of grades I–II and 13.6 of grades III–IV, bilaterally absent in 11.5 of grades I–II and 54.6 of grades III–IV. Baseline bilateral LL m-MEPs were recordable bilaterally in 97.4 % of grades I–II and in 40.9 % of grades III–IV, unilaterally in 2.6 of grades I–II and 40.9 of grades III–IV, bilaterally absent in 18.2 of grades III–IV.

The caudal D wave was recordable in 96.2 % of grades I–II and in 100 % of grades III–IV.

The most frequent IOM setting was represented by a caudal D wave associated with both bilateral lower limb LLm-MEPs and ptn-SEPs (68 procedures), followed by caudal D wave and bilateral (12 procedures), or unilateral (6) LLm-MEPs. The D wave was the only recordable neurophysiologic parameter in three surgical procedures. Other combinations are reported in Table 4.

No monitoring changes were observed in 79/100 of the procedures and none of these subjects had postoperative deficits. Therefore, the number of procedures with transient, or persistent modifications was 21, 19 of which were persistent and 2 transitory (Table 5).

In two cases (all of them affected by IMSCT) the modifications were persistent loss of SEPs after myelotomy, with stable MEPs (both D wave and m-MEPs).

In 16 surgical procedures, a transitory (2 cases), or a persistent loss, or a marked amplitude reduction of lower limb m-MEPs was observed (14 cases), either isolated or in association with a modification of ptn-SEPs (Figs. 1, 2).

**Table 3** Neurophysiologic parameters in 100 procedures for diagnosis and motor status

	ptn-SEPs			m-MEPs			Caudal D wave	
	Bilateral	Unilateral	Absent	Bilateral	Unilateral	Absent	Present	Absent
<b>Diagnosis</b>								
IMSCT	18 (78.3)	1 (4.3)	4 (17.4)	23 (100)	0	0	20 (87)	3 (13)
EMSCT	39 (72.2)	3 (5.6)	12 (22.4)	47 (87)	6 (11.1)	1 (1.9)	54 (100)	0
Myelopathies	17 (73.9)	1 (4.3)	5 (21.7)	15 (65.2)	5 (21.7)	3 (13)	23 (100)	0
	74	5	21	85	11	4	97	3
<b>Preop McKormick</b>								
I–II	67 (85.9)	2 (2.6)	9 (11.5)	76 (97.4)	2 (2.6)	0	75 (96.2)	3 (3.8)
III–IV	7 (31.8)	3 (13.6)	12 (54.6)	9 (40.9)	9 (40.9)	4 (18.2)	22 (100)	0
	74	5	21	85	11	4	97	3

**Table 4** IOM setting in 100 procedures: correlation with aetiological diagnosis and motor status

	Techniques	Diagnosis				Pre-operative McKormick	
		Total	IMSCT	EMSCT	MIELO	I–II	III–IV
a)	DW, m-MEPs bil, SEPs bil	68	15 (65.2)	38 (70.4)	15 (65.2)	62 (79.5)	6 (27.3)
b)	DW, m-MEPs bil	12	4 (17.4)	8 (14.8)	0	9 (11.5)	3 (13.6)
c)	DW, m-MEPs unil	6	0	3 (5.6)	3 (13.0)	0	6 (27.3)
d)	DW	3	0	1 (1.9)	2 (8.7)	0	3 (13.6)
e)	DW, m-MEPs unil, SEPs unil	3	0	2 (3.7)	1 (4.3)	0	3 (13.6)
f)	m-MEPs bil, SEPs bil	3	3 (13.0)	0	0	3 (3.8)	0
g)	DW, m-MEPs bil, SEPs unil	2	1 (4.3)	1 (1.9)	0	2 (2.6)	0
h)	DW, m-MEPs unil, SEPs bil	2	0	1(1.9)	1 (4.3)	2 (2.6)	0
i)	DW, SEPs bil	1	0	0	1 (4.3)	0	1
		100	23	54	23	78	22

DW caudal D wave, *bil* bilateral, *Unil* unilateral

**Table 5** Intraoperative changes

No.	Pt	Diagnosis	Baseline recording			Intraoperative changes	Postoperative motor status
			Ptn SEPs	LL m-MEPs	D wave		
1	DA, m, 19	IMSCT	+	+	+	Bilateral m-MEPs and SEPs loss	Transient deficits
2	VC, f, 15	IMSCT	+	+	+	Bilateral m-MEPs and SEPs loss	Transient deficits
3	PA, f, 59	IMSCT	+	+	+	Bilateral SEPs loss after myelotomy	No new deficits
4	VC, m, 36	IMSCT	+	+	+	m-MEPs loss on one side, deterioration on opposite side	Transient deficits
5	RA, m, 49	IMSCT	+	+	+	Bilateral m-MEPs loss	Transient deficits
6	GE, f, 9	IMSCT	+	+	+	Bilateral m-MEPs and SEPs loss	No new deficits
7	DM, f, 73	IMSCT	–	+	+	Bilateral m-MEPs loss	Transient deficits
8	PG, f, 3	IMSCT	–	+	+	m-MEPs loss on one side, deterioration on opposite side	No new deficits
9	MA, m, 49	IMSCT	+	+	+	Bilateral SEPs loss after myelotomy	No new deficits
10	PE, f, 67	IMSCT	–	–	+	Transitory m-MEPs loss	No new deficits
11	LG, f, 29	IMSCT	+	–	+	Unilateral SEPs loss	No new deficits
12	CM, m, 33	IMSCT	+	+	–	Bilateral m-MEPs loss	Persistent deficits
13	PA, m, 46	IMSCT	+	+	–	Bilateral m-MEPs loss	Persistent deficits
14	IG, m, 37	IMSCT	+	+	–	Bilateral m-MEPs loss	Transient deficits
15	SA, f, 65	EMSCT	–	±	+	Unilateral m-MEPs loss	Transient deficits
16	BCM, f, 62	EMSCT	–	–	+	m-MEPs reappearance	Improved
17	AG, f, 48	EMSCT	+	+	+	Transitory SEPs and m-MEPs deterioration	Transient deficits
18	DM, f, 80	EMSCT	–	–	+	m-MEPs reappearance	Improved
19	MM, m, 75	EMSCT	+	+	+	Transitory SEPs and m-MEPs deterioration	No new deficits
20	DMP, f, 42	MYELO	+	+	+	Bilateral m-MEPs and SEPs loss	Transient deficits
21	OMO, f, 69	MYELO	–	–	+	D wave increase in amplitude	Improved

+ present, – absent, ± unilaterally present

In three cases (affected by IMSCT), baseline D wave was absent and LLm-MEPs disappeared during surgery. Postoperatively, one patient showed transient paraparesis and 2/3 had persistent major motor deficits. In the remaining 13 procedures, a transient, or persistent deterioration of LL m-MEPs with stable caudal D wave, was observed. No postoperative motor deficit was observed in five cases, whilst eight patients presented transient postoperative motor signs. In three cases an intraoperative improvement of MEPs was observed: in 2/3, m-MEPs reappeared, or improved (Fig. 3) and in one case the D wave amplitude increased (baseline ptn-SEPs and LL m-MEPs were absent—Fig. 4).

Therefore, in five cases, the D wave did not provide relevant data as to motor outcome:

In two cases because of the persistent stability of LL m-MEPs;

In three cases because of the caudal D wave was absent

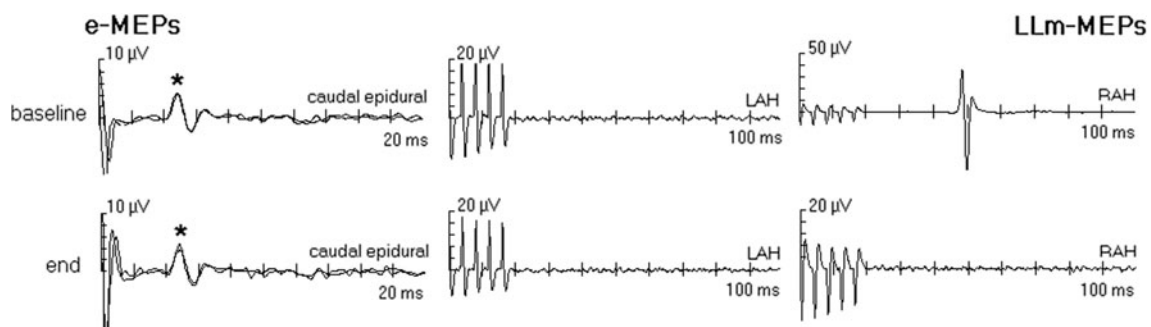
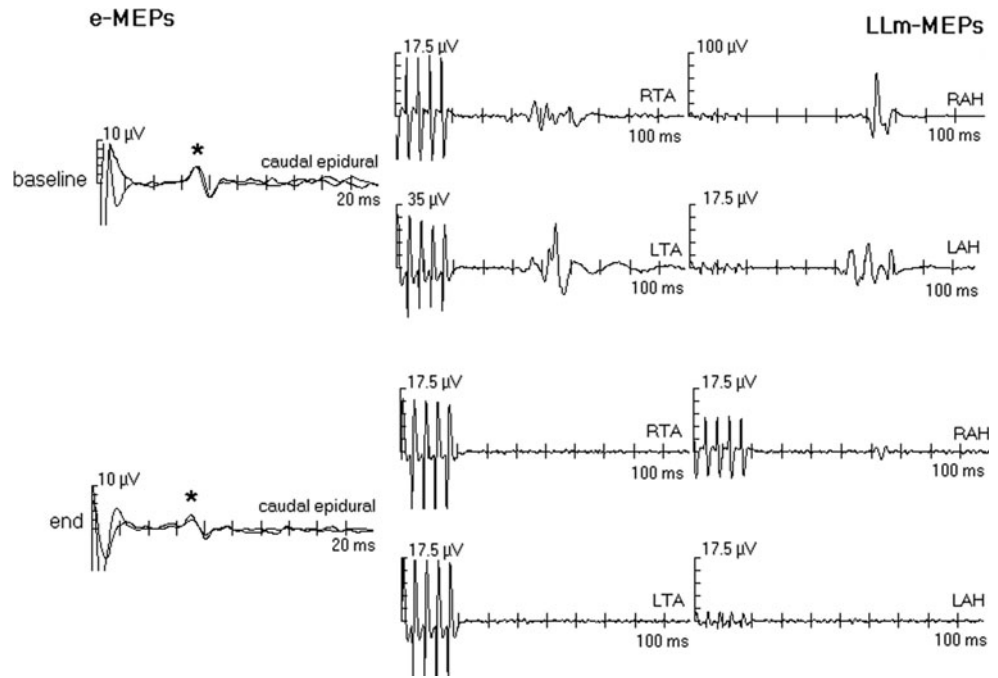
In 16 cases, the impact of the intraoperative D wave was significant:

In 13 cases a stable caudal D wave predicted no new deficit, or transient postoperative motor deficits in case of loss/deterioration of LL m-MEPs

In three compromised patients the caudal D wave predicted the intraoperative reappearance of LL-mMEPs and/or a postoperative improvement.

Briefly, a stable caudal D wave correctly predicted the motor outcome in all cases, even when baseline LL-mMEPs were or in the presence of intraoperative loss/deterioration. When considering the aetiologies, the D wave adds a relevant prognostic value in 9/14 intraoperative modification in IMSCT, as in the remaining cases the modifications were limited to ptn-SEPs, or the D wave was either absent, or

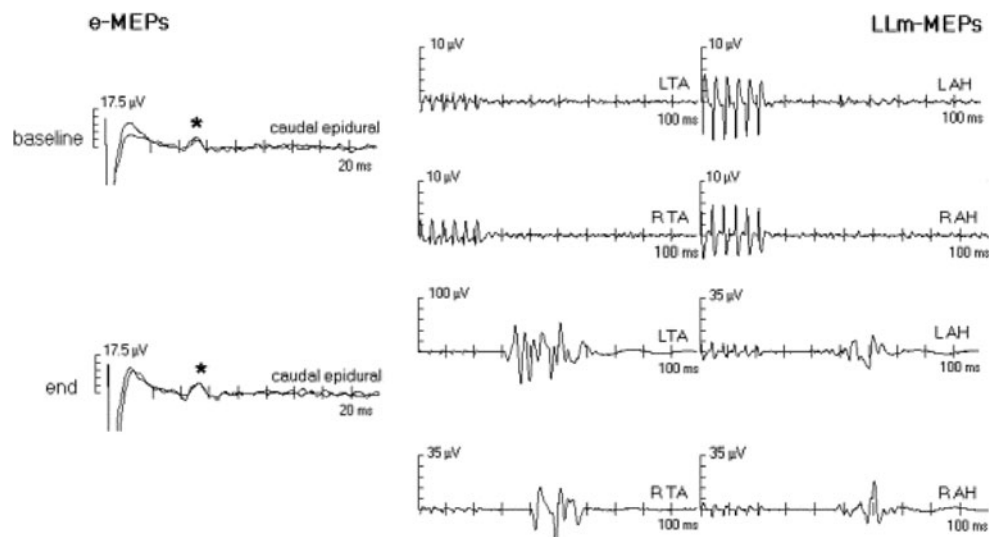
**Fig. 1** IOM of patient #4, affected by cervico-dorsal IMSCT. Despite intraoperative loss/deterioration of LLm-MEPs, associated with D wave (asterisk) amplitude reduction of 40 %, the patient awoke with a mild paraparesis and recovered within 48 h. *RTA* right tibialis anterior, *RAH* right abductor hallucis, *LTA* left tibialis anterior, *LAH* left abductor hallucis

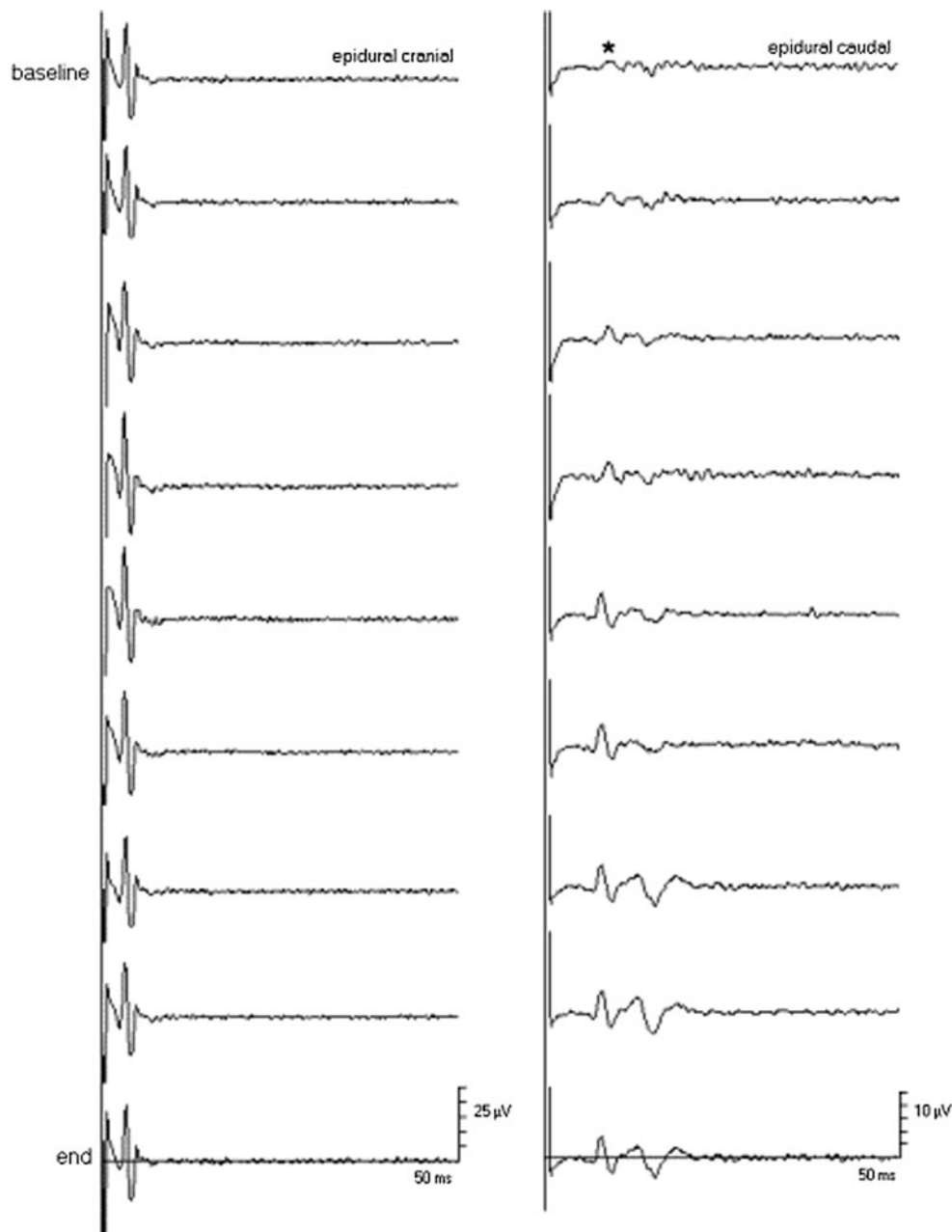


**Fig. 2** Intraoperative loss of right LLm-MEPs in a compromised patient (#15, Table 5), affected by EMSCT, with baseline absent left LLm-MEPs and ptn-SEPs. The caudal D wave (\*) was recordable and

remained stable during the surgical manoeuvres. The patient awoke with a worsening of pre-existing paraparesis and quickly improved. *RAH* right abductor hallucis, *LAH* left abductor hallucis

**Fig. 3** Intraoperative reappearance of LLm MEPs, in a severely compromised patient affected by a dorsal meningioma (#18). Baseline ptn-SEPs were absent. The patient improved quickly in the postoperative period. *RTA* right tibialis anterior, *RAH* right abductor hallucis, *LTA* left tibialis anterior, *LAH* left abductor hallucis





**Fig. 4** Intraoperative increase in amplitude and latency shortening of caudal D wave (*asterisk*) in patient 21, where surgery was performed for the removal of a spinal cervical epidural haematoma. The patient

was paraparetic 24 h before surgery. Baseline SEPs and LLm-MEPs were absent. The patient recovered

chronodispersed. In the remaining diagnostic categories, the impact of D wave was relevant, both in EMSCT (5/55) and myelopathies (2/25), although intraoperative modifications were less frequent than in IMSCT.

## Discussion

Transcranial MEPs significantly improved the intraoperative testing of spinal cord function. Nowadays, the

combined recording of SEPs and MEPs has become a well-established method for intraoperative testing of spinal cord function in complex spine and/or spinal cord surgery (see ref. [7] for a comprehensive review). Although there is general agreement as to the methodology to elicit both e-MEPs and m-MEPs, controversies do persist as to the indications for IOM with both e-MEPs and m-MEPs [6, 10–16].

Numerous studies have proposed that a combined recording of epidural and muscle MEPs be carried out

during IMSCT surgery [6, 10–13] to predict motor outcome in the presence of deterioration/disappearance of LLm-MEPs, however, not all agree [14–16].

Indeed, muscle MEPs may be completely lost during surgery for intramedullary spinal cord tumours but, if the D wave amplitude is either stable, or decreased by less than 50 %, then although the patient will present additional transient motor deficit postoperatively, motor strength will be recovered in terms of post-surgery hours or days [17].

This phenomenon has been defined as “surgically induced transient paraplegia” [17] and is most likely attributable to the reversible inactivation of noncorticospinal descending tracts and the propriospinal system, whilst fast-conducting corticospinal fibres are mostly preserved [17].

If the intraoperative assessment of motor pathways is limited to the m-MEPs, an intraoperative disappearance/deterioration of m-MEPs can be followed by persistent, or transient motor deficit [14–16]. This fact has led to the using of the term *false positive*, which may be confusing as this refers to m-MEPs that should be considered as only a part, though relevant, of the intraoperative assessment of motor function.

Indeed, the D wave amplitude is a direct measure of the number of functioning fast-conducting fibres in the corticospinal tracts [8]. Since no synapses are involved between the stimulating and the recording site (the proximal axon of the cortical motoneuron is stimulated and the recording site is located below the lesional site, but above the synapses at the alpha-motoneuron), the D wave has been considered the gold-standard in the assessment of the integrity of the cortico-spinal tract [17].

As m-MEP generation depends on the excitability of facilitatory cortical motor neurons, beyond the spinal cord conductivity and the excitability of lower motoneurons, they represent the correlate of not only the cortico-spinal but also of the non-corticospinal tract motor pathways.

In our series, the caudal D wave was the most recordable intraoperative neurophysiologic parameter, particularly in compromised patients, even in cases where baseline LLm-MEPs were unilaterally, or bilaterally absent. Furthermore, the impact of the intraoperative recording of the D wave is relevant in a large percentage of surgical procedures. Indeed, a persistent stability of the caudal D wave is predictive of a good motor outcome, even when the LLm-MEPs are intraoperatively abolished, or diminished. This is particularly true for IMSCT, and also in the other categories studied.

If in our study the intraoperative assessment of motor tracts was limited to m-MEPs, all patients with transient postoperative motor deficit were considered as “false” positive. Conversely, the combined recording of D waves and LLm-MEPs reduces the number of *false positives* to zero.

Interestingly, in our series, all the three IMSCT patients without a clear caudal D wave intraoperatively lost m-MEPs and two of them presented persistent neurological deficits at follow-up. As there is evidence that SEPs and muscle MEPs are more sensitive to intraoperative spinal cord ischaemia than is the D wave [20], the IOM protocol does not generally include e-MEPs when the risk of spinal cord damage is thought to be ischaemic. However, in the presence of LL m-MEP deterioration, the caudal D wave provides the opportunity to check the cortico-spinal tract function, while countermeasures are taken to avoid persistent spinal cord damage.

The lateralizing value of the D wave is generally considered poor because of the midline recording and the difficulty to restrict the stimulation to a single hemisphere [18]. However, in compromised patients where the multi-pulse technique may fail to evoke unilateral, or bilateral LLm-MEPs, the caudal D wave may represent the correlate of still functioning fibres of both cortico-spinal tracts. Therefore, it is reasonable that monitoring the D wave may contribute to reducing further damage in an already compromised patient.

As aforementioned, in two cases, the recordability of the caudal D wave was associated to an intraoperative reappearance of LLm-MEPs and, in a third case, an increase in amplitude and latency shortening of the caudal D wave was observed. These intraoperative data were associated to a postoperative improvement of motor status. Although the primary scope of IOM is to prevent any iatrogenic injury, an intraoperative improvement is of primary relevance, not only from a prognostic point of view but also for a correct planning of rehabilitation strategy.

Finally, although this study has demonstrated that MEPs were percentually more recordable than are SEPs for our series, SEPs do retain a great value in assessing dorsal column function, such as proprioception, which is of paramount importance even for locomotion. Moreover, although there is still some concern about D wave recording as it is invasive, intraoperative techniques, in particular transcranial electrical stimulation and spinal epidural recording electrodes are generally considered safe when in the hands of a skilled IOM team [18]. None of our patients reported any of the iatrogenic complications that have been described in literature [18] i.e. injury, infection due to electrode placement, spinal epidural haematomas following insertion of epidural electrodes, neurological complications associated with transcranial motor cortex stimulation and seizures.

In conclusion, our study provides further evidence as to the relevance, impact and safety of epidural motor evoked potentials in spine and spinal cord surgery.

On the basis of our results and personal experience, we are of the opinion that not only should intraoperative D



wave recording be considered mandatory in IMSCT surgery but that it should also be attempted in other types of spine and spinal cord surgical procedures, particularly for compromised patients with absent, or poorly defined LL m-MEPs.

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**Conflict of interest** None.

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