

## Intraoperative Neurophysiological Monitoring for Spinal Cord Surgery

a report by

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Knowing the functional integrity of the spinal cord during surgery is an intriguing concept that was first probed by orthopaedic surgeons three decades ago. Sensory-evoked potentials (SEPs) were available then, but with, from today's perspective, a rather primitive technology. Furthermore, SEPs reflect the functional integrity of the sensory pathways. Information about the more important motor pathways was only indirect. This may be acceptable when external cord compression is the expected mechanism of injury, and it has indeed been shown to be effective in an extensive retrospective study of scoliosis surgery.<sup>1</sup> The resection of lesions within the substance of the cord is more complex. It carries a risk of selective damage to the motor tract, which may not be reflected by SEP changes,<sup>2</sup> and SEPs can even be recordable in paralysed individuals prior to surgery.<sup>3</sup> Moter-evoked potential (MEP) monitoring is based on the cumulative understanding of the motor system acquired since the 1950s,<sup>4,5</sup> when a small but essential fibre population in the corticospinal tract was identified and found to give rise to a recordable travelling wave, then termed the D-wave. After the development of transcranial electrical motor cortex stimulation in humans,<sup>6</sup> this knowledge was applied in the operating room.<sup>7,8</sup> Muscle recording techniques<sup>9</sup> were hampered by the effects of general anaesthesia on the  $\alpha$ -motor neurons. This was resolved by the multipulse stimulation technique.<sup>10</sup> Thus, two techniques to monitor the functional integrity of the motor system are now available: the D-wave and muscle MEPs. The practical application of these in various types of spine and spinal cord surgery were refined during the 1990s.<sup>3,11–14</sup> More recently, very strong evidence for the benefit of MEP monitoring for spinal cord surgery was reported.<sup>15</sup>

### Neurophysiology

Motor potentials are evoked with transcranial (through the skin and skull) electrical stimulation of the motor cortex of the brain. Electrical stimulation is then performed with rectangular constant current impulses of 500 $\mu$ s duration and intensities between 15 and 200mA. Individual stimuli elicit D-waves,<sup>4</sup> which can be recorded directly from the spinal cord caudal to the site of surgery. Depending on the level

on the spinal cord where the recording electrode is placed, the latencies are quite short, never exceeding 20ms. Baseline recordings are obtained before the opening of the dura. The stimulations are repeated at a rate of 0.5–2Hz during the critical part of the procedure. This provides fast, 'online' feedback. The important D-wave parameter is its amplitude. A decrease of more than 50% of the baseline value is associated with a long-term motor deficit.<sup>16</sup> Latency changes of the D-wave are rare and are the result of non-surgical influences such as temperature.<sup>17</sup> Higher stimulation intensities lead to shorter latencies, implying that the corticospinal fibre activation occurs deeper in the white matter of the brain.<sup>7</sup>

Muscle MEPs are elicited in the same way, although not with single stimuli but with a short train of five to seven stimuli with 4ms interstimulus intervals.<sup>18,19</sup> Therefore, this is called the multipulse technique.<sup>14</sup> Compound muscle action potentials are recorded with needle electrodes from target muscles in all four extremities (thenar, anterior tibialis and abductor hallucis). Other muscles, such as the quadriceps, hamstrings, biceps or the diaphragm, and even the anal sphincter, can be used if required. Realtime feedback is possible here as well, and in most cases is even easier than the D-wave. Muscle MEPs are recorded in an alternating fashion with D-waves. An individual electrical stimulus on the motor cortex, either with exposed cortex or transcranial stimulation,<sup>20</sup> elicits a D-wave in the corticospinal tract. A fast train of five stimuli at 250Hz elicits five D-waves, which then travel down the corticospinal tract 4ms apart. The spinal  $\alpha$ -motor neurons are hit by five consecutive D-waves elevating their membrane potential above firing threshold.<sup>5</sup> The parameter monitored is the presence or absence of muscle MEPs in the target muscles within a stimulus intensity range of approximately 15–200mA. This all-or-nothing concept has been adopted because of the tremendous variability of muscle MEP amplitudes<sup>11,21,22</sup> and because a motor deficit occurred only when the muscle response was lost.<sup>3,9,11,22</sup> To define a threshold amplitude below which one expects an intraoperative injury<sup>14</sup> is difficult, even though it appears logical that a stimulus threshold increase vis-à-vis stable anaesthetic depth may indicate some degree of subclinical injury.

### Anaesthesia

Anaesthesia management,<sup>23</sup> which allows intraoperative monitoring, particularly of MEPs, consists of a constant infusion of propofol (usually in a dosage of about 100–150 $\mu$ g/kg/min) and fentanyl (usually around 1 $\mu$ g/kg/h). The use of propofol for anaesthesia with MEP monitoring has been reported with various stimulation techniques.<sup>24–28</sup> Nitrous oxide not exceeding 50 vol.% can be used. Bolus injections of both intravenous agents should be avoided because this temporarily disrupts muscle MEP recordings, which is particularly problematic during the critical resection part of the operation. Short-acting muscle relaxants are given for intubation but not thereafter. Halogenated



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anaesthetics should not be used,<sup>10</sup> as they elevate muscle MEP stimulus thresholds and block muscle MEPs in a dose-dependent fashion.<sup>29</sup> Using them would add an uncontrollable variable. Partial myorelaxation is used by some groups,<sup>22</sup> but its use combines poor anaesthesia with poor monitoring.

### Safety

Apart from direct neural tissue damage,<sup>10,30</sup> the primary concern with the use of transcranial electrical multipulse stimulation is the issue of seizures. All data reported so far, as well as the theoretical concept of transcranial electrical stimulation with a short high-frequency train to elicit muscle MEPs, indicate an extremely low risk of inducing seizures. The term 'kindling' has been indiscriminately used in this context. Kindling is an experimental model referring to the induction of a self-perpetuating epileptic focus in the brains of experimental animals. This would require frequent and repeated electrical stimulation with 50Hz for several seconds. This differs significantly from the MEP train stimulation paradigm of 250Hz for 25ms.<sup>31</sup> Furthermore, the energy necessary to induce a seizure with electroconvulsive therapy (also with 50Hz stimulation applied for several seconds) is two orders of magnitude higher than the overall energy used for MEP monitoring.<sup>32</sup> Adverse events that sometimes occurred were minor lacerations and haematoma of the tongue as a result of strong contraction of the masticatory muscles due to direct stimulation from the cranial stimulation electrodes. This can be avoided with tongue protection and a padded airway protector. No complications such as injury or infection due to electrode placement or stimulation and no spinal epidural haematomas resulting from placement of epidural electrodes have been reported.

### Correlation Between Monitoring and Clinical Status

Pre- and post-operative motor function, as assessed with the McCormick scale,<sup>33</sup> correlates well with the intraoperative D-wave and MEP data.<sup>3</sup>

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### Interpretation of D-wave

The important parameter in D-wave interpretation is its peak-to-peak amplitude. The monitorability of the D-wave and the intraoperative significant decline of its amplitude have been shown to be of predictive value for the motor outcome after intramedullary surgery. Patients in whom the baseline D-wave recording produces no response have a higher risk of post-operative motor deficits than those with a recordable D-wave.<sup>16</sup> Whether this is due to an inherent subclinical damage and vulnerability of the motor tract or to the fact that there was no monitoring support for the surgery is not known. The explanation for the absence of a recordable D-wave in an individual with intact motor function (and recordable muscle MEPs) is believed to be the result of chronic damage to the corticospinal tract, resulting in a desynchronisation of the wave. This is frequent after prior surgery

with extensive tumours and prior radiation therapy. The intraoperative amplitude decrease of the D-wave correlates with post-operative outcome. If the D-wave is unchanged, there is no lasting post-operative deficit. If it declines by more than 50% of the baseline value or disappears, paraplegia ensues.<sup>16,34</sup>

### Interpretation of Muscle Motor-evoked Potentials

The presence of muscle MEPs always indicates intact functional integrity of the corticospinal tract. Occasionally, in patients with a moderate motor deficit it may be difficult to obtain recordings from both lower extremities.

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If that occurs, responses in the weaker leg usually require higher stimulation intensities. Intraoperative preservation of muscle MEPs means intact motor function post-operatively in all cases. Intraoperative loss of muscle MEPs indicates some post-operative impairment of voluntary motor control with a specificity of about 90%. For instance, muscle MEPs lost in one leg during the resection means that the patient will post-operatively be unable to move this extremity for a limited period of time. This is called a temporary motor deficit. Loss of muscle MEPs in both legs indicates bilateral motor deficit. Unilateral loss is of less concern, as it has been shown in the past that unilateral motor disruption always recovers with a mechanism whereby the intact side 'takes over' control of the affected side.

### Combined Interpretation of D-wave and Muscle Motor-evoked Potentials

The D-wave amplitude is a measure of the number of fast-conducting fibres in the corticospinal tract. If 50% of these fibres are damaged by the procedure, the amplitude will decrease to 50% of its baseline value. Based on practical experience, D-wave decrease usually occurs in small increments, going down by 15%, 20%, 30% and so forth. By and large, D-wave amplitude decrease is associated with loss of muscle MEPs. However, it may be that muscle MEP loss occurs without a D-wave amplitude decrease, or that the D-wave decreases without changes in muscle MEPs. Preservation of the D-wave above the 50% cut-off value has been found to be predictive of long-term preservation (or recovery) of voluntary motor control in the lower extremities. With loss of muscle MEPs and preserved D-wave amplitude, a temporary motor deficit is expected post-operatively. In this situation, it is still safe to complete a resection or to pause and wait for recordings to improve, which they often do. This situation is the window of reversible change, which allows for a change in surgical strategy before irreversible injury has occurred.

### Use of Monitoring Information for the Surgeon

Intraoperatively, the combined data of epidural and muscle MEPs indicate some effect of the surgical manipulation on the functional integrity of the motor pathways at some point during the procedure in almost every other patient. In about one-third of patients these

changes remain until the end of the operation and then correlate to a temporary motor deficit. In the remainder of cases, the changes are reversible during surgery; this correlates to intact motor function when the patient awakens from anaesthesia.

- Stable recordings: the presence of robust and stable full recordings of D-wave and muscle MEPs allows for swift, safe and complete resection of a spinal cord tumour. This is particularly useful, as it removes uncertainty about the safety of some seemingly dangerous manipulations.
- Small MEP change: some loss of muscle MEPs or a non-significant change of D-wave amplitude may prompt the surgeon to halt the procedure, wait and irrigate the cavity, and this often normalises the recordings quickly, allowing the procedure to continue. Sometimes the site of dissection may have to be changed, or a particular area must be treated with special attention.
- MEP change indicating temporary motor deficit: if sustained loss of some muscle MEPs unilaterally or bilaterally has occurred, the surgeon must stop. Again, irrigation and waiting must be employed, and sometimes an elevation of mean arterial pressure may be necessary. Often, it takes 20–30 minutes until the recordings recover. If they do, the surgery continues; if they do not, the decision has to be made as to whether continuation in the interest of complete tumour resection is acceptable or whether the surgery should be halted and staged for a second operation.
- Stopping surgery: MEP change and complete loss of muscle MEPs

and 50% D-wave amplitude decline indicate the limit of the pattern for temporary motor deficit must prompt a stop of the surgery. A second operation will be necessary if significant tumour mass had to be left behind.

- Use of special instruments during surgery: the ultrasonic aspirator is an essential neurosurgical instrument for tumour debulking. However, its use to debulk still *in situ* tumour mass in the spinal cord frequently leads to damage of motor pathways, as picked up by monitoring. Therefore, it must be used very carefully, probably only to get partly dissected tumour out of the way, but never at the edge of the tumour near the cord interface. The microsurgical laser, often looked upon suspiciously by many neurosurgeons, is a superb neurosurgical instrument for spinal cord surgery and does not create an electrical artifact, which would disturb electrical recordings. Therefore, it is much more useful to use the laser rather than the traditional ‘bipolar and suction’ technique.

## Conclusion

Intraoperative monitoring with MEPs is useful in neurosurgical practice. During surgery of spinal cord tumours, this set of techniques is probably best tested and has yielded most practical experience. Today, this type of monitoring is essential in such critical neurosurgery. Monitoring with MEPs and many other neurophysiological techniques and modalities is also useful in many other types of neurosurgery, such as surgery in the cerebellopontine angle, for aneurysms, of the brainstem and in the cauda equina. Monitoring has its place in the neurosurgical operating room, as does neuroanaesthesia. ■

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