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Recent developments in neurosurgical spinal cord monitoring

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In a review 8 years ago, the then current status of intraoperative spinal cord monitoring (SCM) was discussed.[1] Concerning future developments, that article concluded that the major challenge lay in (a) the improvement of the reliability and clinical relevance of somatosensory evoked potential (SEP) monitoring, where the incidence of false-negative and false-positive results had to be reduced, and (b) the application of new techniques like motor evoked potential (MEP) monitoring, which might turn out to be a method complementary to the SEP approach.

Since that time, there has been a considerable amount of newly published results from intraoperative SCM, although clinical articles on exclusively neurosurgical SCM are rare (Table I). A selective literature search for the present review (primarily for the time from 1988 to 1992) yielded more than 200 citations. Eighty-one studies entered into the final evaluation; among these were 3 conference proceedings,[15–17] 6 book chapters,[7,11,18–21] and 10 review articles.[22–31] Further, 40 clinical articles, and 22 articles on experimental work were counted. In particular, experimental studies in animals have given support to clinical monitoring by exploring the usefulness of new stimulation and recording techniques.[24] This reappraisal only considers recent work on SEP and MEP in neurosurgical SCM with some experimental studies relevant to clinical SCM. Spinal cord monitoring in orthopaedic surgery is not evaluated in this review for reasons detailed in the article.

Key words: spinal cord monitoring; somatosensory evoked potentials; motor evoked potentials.

SEP monitoring

Different techniques

Neurosurgical SEP monitoring has increasingly been carried out with spinal rather than scalp recording, although in accordance with previous studies,[19] noninvasive SEP recording from the scalp[10,12,32] and from Erb's point and neck[33] in various neurosurgical procedures was also found to be useful. A new approach can be seen in the use of dermatomal SEP, latencies of which appeared to be reliable indicators of adequate lumbar nerve root decompression intraoperatively.[34] Cervical dermatomal SEP and SCEP after finger stimulation[35] may become a helpful device for intraoperative electrodiagnosis or monitoring of decompression procedures in cervical spinal surgery. As for spinal recordings, two methods are to be distinguished. *Conductive* spinal cord evoked potentials (SCEP) can be obtained from levels clearly above the lesion site after peripheral or spinal ('spinally evoked conductive SCEP') stimulation.[36] The latter approach is discussed below in the context of other spino-spinal techniques. *Segmental* SCEP are recorded near the lumbosacral or cervical enlargement after lower or upper extremity nerve stimulation.[36] A disadvantage of this method is the variability of responses dependent on even slight changes of the recording electrode position.[37] Romstöck[9] found that while SCEP in thoracolumbar spinal cord surgery were variable and often (48%) gave false-positive results, cervical recordings were more stable (0% false-positives). Since spinal recordings are less susceptible to anaesthesia effects and require less runs per average than cortical

Table I Recent clinical studies on spinal cord monitoring in neurosurgical operations

1st author	Year of publication	No of patients	Diagnoses	SCM modality	Recording sites
Baba[2]	1988	36	Various spinal cord diseases	SCEP	Epidurally
Fukui[3]	1991	19	Spinal cord tumours	SCEP	Spinal cord, peripheral nerve
Inghilleri[4]	1989	10	Thoracic spinal cord tumours; pain syndromes	MEP	Epidurally C7–Th5
Jellinek[5]	1991	34	NpP; spinal cord tumours	MEP	Muscle
Levy[6]	1987	45	Cervical discopathy etc	MEP	Spinal cord, nerve, muscle
Matsuda[7]	1989	226	Mixed orthopaedic and neurosurgical (tumours etc)	SCEP, MEP	Epidurally, nerve
McDonnell[8]	1988	4	Cervical myelopathy	SEP	Scalp
Romstöck[9]	1988	28	Various cervical and thoracic lesions	SEP	Epidurally
Schramm[10]	1986	25	Spinal cord tumours	SEP	Lumbar, cervical, and cortical levels
Tamaki[11]	1989	500	Mixed orthopaedic and neurosurgical (tumours etc)	SCEP	Spinal cord (various levels)
Watanabe[12]	1988	63	Various spinal cord diseases	SEP	Epidurally; scalp
Yokogushi[13]	1991	14	Spinal cord tumours	SCEP	Spinal cord above lesion
Zentner[14]	1989	50	Various spinal cord diseases	MEP	Muscle

SEP, this approach is worth pursuing. Finally, it was found that SEP monitoring in dorsal root entry zone (DREZ) lesion procedures for pain relief could predict permanent postoperative neurological deficits[38] and indicate the extent of histologically defined lesions after DREZ thermal radiofrequency treatment.[39]

Determination of significant changes

Since SCM can only be accepted if it is of benefit to a considerable proportion of patients monitored, the criteria of significant intraoperative SEP changes must be stated as the basis of a rationale for the adjustment of operative strategy to monitoring data.[26,40] Due to the variability of intraoperative recordings,[9,41,42] the criteria of clinically significant changes have mostly been determined retrospectively and arbitrarily.[40] Amplitude and latency changes are still the parameters most commonly considered in the determination of alarm and intervention criteria.[29] The further consideration of parameters like wave configuration[26] or conduction of repetitive stimuli[43] has not become routine practice. Dependent on the clinical characteristics of the patients monitored and on the stimulation and recording techniques, amplitude decrements between 20%[42] and 60%[26] and latency increases between 4%[44] and 10%[9] were found to be associated with the occurrence of postoperative neurological deficits. In patients with neurological disorders, intraoperative responses are particularly variable.[9,41,42] Since there is still a lack of generally accepted monitoring standards, every clinic must identify and use its own intervention criteria in a series of operations.[19,29] Evidence for the benefits of SCM is often more conclusive in reports of single cases rather than in the evaluation of larger patient groups. Daube,[45] for example, presented a patient in which reversal of damage occurred during fusion of a traumatic cervical spine fracture, where SEP changes indicated spinal impairment due to excessively tight wires intraoperatively. However, the efficiency of such modifications of surgical strategy cannot be proven unless there are control groups without monitoring or even, paradoxically enough, with monitoring that is ignored by the surgeon. Finally, the problem of false-negative and false-positive records has not yet been resolved. Whilst false-negatives are rare but of great consequence, false-positives can occur in up to 20% of monitoring procedures.[29] With improvement of technology and standardisation of warning and intervention criteria, the proportion of false-positives and false-negatives can be expected to diminish.

MEP monitoring

Methodological aspects

The need for motor tract monitoring is obvious, since SEP are not sensitive to deterioration of anterior spinal pathways.[46,47] MEP studies in animals have suggested that responses to motor tract stimulations are well correlated to experimentally induced spinal cord lesions.[48–51] Stimulation can be electrical or magnetic, transcranial, cortical, or spinal;[31] responses are obtained from muscles, peripheral nerves, or the spine (spino-spinal techniques are discussed below). MEP monitoring is much more easily compromised by the negative effects of general anaesthesia and relaxants than are SEP, but responses under nitrous oxide[52–54] or propofol[55,56] anaesthesia have been described as sufficient for a regular monitoring procedure. Furthermore, muscle responses can be efficiently facilitated by additional peripheral nerve stimulation, however, the necessary quantification of its degree proves to be difficult.[57,58] Generally, electrical stimulation is preferred for its direct impact on the corticospinal tract (D-wave), although high intensity magnetic stimulation may also activate the pyramidal axons directly.[59,60] Further, spinal responses seem to be less susceptible to the effects of anaesthesia than are peripheral ones,[61] and prove to be less susceptible to spinal cord alteration than are peripheral nerve and muscle recordings.[6]

Clinical studies

As for the few clinical reports, Jellinek *et al*[5] successfully monitored 7 out of 8 patients with spinal tumours or arteriovenous malformations and abnormal preoperative motor conduction. They found that permanent loss of MEP (recorded from the dorsal interosseus muscles after transcranial electrical stimulation) was associated with postoperative neurological impairment (one patient), while reversible amplitude and latency changes did not indicate deterioration in neurological function. Similar results were obtained by Kitagawa *et al*,[62] who recorded epidurally (Th4–Th12) after transcranial stimulation in cervical spine orthopaedic surgery (n = 20; one patient with quadriplegia after total loss of MEP). Zentner[14] presented a larger series of 50 patients with various spinal cord diseases, 43 of whom were monitored successfully. Responses were obtained from thenar and anterior tibial muscles after transcranial electrical stimulation, and amplitude decrement up to 50% was considered acceptable. On the basis of these conventions, there were no false-negative results, and postoperative neurological status was correctly predicted in 81.4% of the anterior tibial muscle recordings and 76.2% of thenar recordings (see Zentner[63] for further results from cauda equina and spinal cord recording). The disadvantage of this technique is the unwelcome occurrence of muscle contractions as a result of high intensity electrical stimulation. Furthermore, it must be appreciated that the special anaesthesia required for regular recording does not lead to undesirable recall phenomena postoperatively. Levy[6] applied multilevel recordings from the ligamentum flavum, peripheral nerves and muscles after transcranial or direct stimulation in 98 cases, 45 of them with spinal cord affections. In these patients, MEP recordings did not miss any postoperative neurological deficits, and in a few cases intraoperative MEP deterioration led to a modification of operative strategy with subsequent recovery of responses.

Conclusion
Intraoperative MEP recording after electrical stimulation requires very special anaesthetic techniques which still have to be developed for transcranial magnetic stimulation. Stimulation methods avoiding strong muscle contractions need improvement. These studies indicate that motor tract monitoring can further be developed and may even work in some patients with impaired baseline recordings, which are frequent in neurosurgery. However, there are very few reports with few patients and even less actual influence of monitoring results on surgical strategy. The mere 'prediction' (often stated retrospectively?) of neurological outcome is academic if the monitoring procedure does not help to avoid complications.

Combined SEP and MEP monitoring

Animal studies
There are several reports on experimental animal studies with combined SEP and MEP monitoring that are also relevant to SCM in clinical practice. In rats with clip compression injury at C8, it was found that MEP are generally more sensitive to injury, whereas SEP more precisely distinguish between different degrees of injury;[64] in this study, transcranially evoked MEP were recorded from the spinal cord and the sciatic nerve. Similarly, in a spinal cord weight drop model in cats, MEP – especially the spinal signal – was more easily affected (impact of 100–150 g/cm) than SEP (200–250 g/cm).[65] On the other hand, muscle MEP after single stimuli in rats are less sensitive to light spinal cord injury than SEP.[66] In a cordorhizotomy model in hogs with cortical or spinal motor stimulation and sciatic nerve recording, MEP failed to indicate sensory tract lesioning, while SEP remained unchanged with severe motor deficits.[67] These experimental studies suggest that MEP and SEP indeed reflect the functional status of the respective spinal pathways and can be used as complementary techniques in clinical SCM.

Clinical studies
Matsuda[7] compared transcranially evoked spinal MEP to cauda-equina-evoked spinal SEP in patients with various spinal cord affections. The course of SCM in 5 operations for intramedullary tumours suggested that SEP and MEP efficiently monitor the respective pathways and that especially the absence of marked changes in MEP – also when combined with major SEP reduction – warrants regular continuation of the operation. In a purely orthopaedic study,[68] 40 patients received combined MEP and SEP (conductive ESCP) monitoring during scoliosis surgery. Although there were neither persistent EP changes nor new neurological deficits, the results were illuminating with respect to the general practicability of combined monitoring: in 7 (18%) of the patients, most of them with preoperative motor deficits, SEP but not MEP could be elicited; in 2 (5%), only MEP were recordable, and 2 patients showed no potentials at all. Due to further technical problems, combined monitoring was successful in a total of 28 (70%) patients.

Conclusion
These results once again indicated that successful SCM is difficult to obtain especially in patients with abnormal baseline recordings, as also stressed previously.[1,23,42] On the one hand, the combination of two monitoring techniques will increase the proportion of failures; on the other hand, monitoring of one modality may be helpful in the case of failure of the other technique. All in all, the combined SEP/MEP SCM looks promising, although far more genuinely clinical studies are required to justify this optimism.

Spino-spinal recordings

Spinal cord potentials can be evoked by ascending[11,69] as well as decending[70,71] volleys after spinal – mostly epidural – stimulation. These techniques have primarily been used for preoperative diagnosis. Clinical[11] and experimental[72] studies indicate that responses to spinal stimulation involve both motor and somatosensory tracts in the spinal cord. For example, electrical spinal stimulation at T7 in the cat results in activity in the L7 ventral and dorsal root, and epidural recording from L3 yields a three-component response with the first two peaks reflecting activity in the ventral pathways and the third one representing dorsal column activation.[72] These data may raise some optimism concerning a combined ascending/descending SCM with rostral and caudal electrodes that can both be used for stimulation and recording.[11] Turning to clinical studies, Yokogushi[13] intraoperatively recorded ascending conductive ESCP in 14 cases of spinal cord tumors. While there were neither false-positive results nor any additional postoperative neurological deficits, recordings were found to be of some value since responses improved after decompression in 6 out of 8 patients with abnormal ESCP, thus anticipating postoperative improvement. A similar technique was applied in 36 patients with various cervical spine diseases.[2] In 7 patients (19%), SCM was not successful; only 2 showed more than 50% amplitude attenuation, but did not develop major new neurological deficits. Altogether, the clinical application of spino-spinal recording in neurosurgical SCM is still in its beginnings. The ideal of a combined ascending/descending SCM could not yet be achieved with that technique. Criteria of significant change (mostly amplitude reduction of more than 50%)[2,13] are somewhat arbitrarily defined. If the procedure works, however, it is elegant and may even do away with time-consuming averaging of signals.

General conclusions and outlook

Although the work reviewed is instructive and revealing in several respects, it will not suffice to establish SCM as a routine monitoring procedure on neurosurgery of the spinal cord. While considerable progress has been made concerning some special applications and recordings and stimulation techniques, the concept of SCM in neurosurgery has still not stood the test of time. This is also due to the fact that there was no successful coordinated effort toward standardisation and unification of SCM procedures, but mainly because many neurosurgical patients have poor, unmonitorable potentials to start with. Up to now, clinical studies have been very heterogenous regarding recording and stimulation sites and techniques and patient selection. Furthermore, there is the problem of the dissociation of relevance and validity of SCM data: in domains like scoliosis surgery, valid results can be obtained in large patient groups without monitoring events and without postoperative neurological deficits; however, in other genuinely neurosurgical domains such as intramedullary tumour surgery, there are smaller series with fluctuating SCM data, sometimes severe pre- and postoperative deficits and deteriorated baseline recordings. But the comparably valid data obtained in the former group are of rather little clinical relevance, while the insecure findings in the latter group might play a genuine role in intraoperative decision making if only they were more reliable and valid. At present, SCM is often completely unsuccessful in problem patients where intraoperative electrophysiological data are desired. Due to these problems in patients with impaired baseline recordings, the application of SCM in neurosurgery in the main is limited. But further progress can be expected if stimulation and recording become more standardised and warning and intervention criteria are stated prospectively; mere 'prediction of outcome' is secondary compared to avoidance of risky surgical manoeuvers. More multilevel recording in both SEP and MEP SCM is desirable in order to determine the optimal recording site. Transcranial and peripheral nerve stimulation techniques are more widely applicable and less invasive than spinal techniques and therefore offer themselves as primary methods with the most realistic prospect of standardisation. Motor tract monitoring is still constrained by various specifically intraoperative recording difficulties which considerably limit the application of this technique. The above critical remarks should not be viewed as defeatist, since we explicitly appreciate some promising approaches, one of which might well result in a major breakthrough within the next few years. After all, SCM is something like 'the only game in town', that is, the only method of continuous intraoperative assessment of spinal functions currently available.

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