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Scientific Review

Intra-operative spinal cord monitoring in orthopaedics

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The surgical correction of spinal deformities carries a small but significant risk of injury to the spinal cord. To detect the onset and possibly reverse the effects of surgical complication, a variety of neurophysiological monitoring procedures can be employed. The purpose of this review is to provide information regarding the various methodologies available for monitoring spinal cord and nerve root function during orthopaedic procedures. Intra-operative monitoring of cortically recorded somatosensory evoked potentials (SEPs) by peripheral nerve stimulation is of value during orthopaedic surgery and is the state-of-the-art in terms of non-invasiveness, versatility, time requirement, lateral discrimination, and ease of electrode placement. Monitoring of motor evoked potentials (MEPs) is useful particularly in combination with SEPs but is still considered investigational. Root function monitoring has limited application and requires more clinical research.
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Introduction

During surgical intervention to correct spinal deformities using metallic fixation there is a risk of neurological damage. Prevention of damage to the spinal cord is very important. Once damage has been done it is often irreversible. Monitoring the nervous system can identify complications early enough so that treatment or correction can be implemented before the impairment becomes permanent.

The frequency of post-operative neurological deficit is well illustrated in the study conducted in 1975 by the Scoliosis Research Society.[1] Out of 7885 operations performed between 1965 and 1971 an incidence of post-operative neurological deficit of 0.72% was found. Approximately half of these patients showed a permanent loss of motor function. There was a relatively large number of patients with congenital scoliosis in the series, and this suggests that congenital scoliosis carries a higher risk of neurological complication than scoliosis from other causes. Moreover, while no particular curve pattern seems especially vulnerable, the presence of severe kyphosis markedly increased the risk of neurological complications. This has been confirmed by a recent study.[2]

With the advent of segmental spinal instrumentation there has been an increased risk of injury to the spinal cord owing to the repeated passage of sublaminar wire through the posterior epidural space. The time of maximum risk is at distraction (mechanical straightening), or during the subsequent closing period.

There is a strong general consensus that at least some form of intra-operative monitoring should be used for cases in which the spinal cord is at risk. The primary purpose of intra-operative monitoring is to detect any deterioration in neurological function resulting from either surgical or perisurgical procedures. The secondary purpose of monitoring is to inform the surgeon if the recovery of the trace has occurred after modifications to the instrumentation.

Until 30 years ago the only method of evaluating the onset of intra-operative neurological deficit was the wake-up test.[3] Described in 1973, the test consists of lightening the anaesthetic state to the point at which the patient can respond to a command. If the patient is unable to move his feet the distraction is reduced and the test repeated until a safe level of distraction is reached. The use of the wake-up test has many well-documented limitations: an inadvertent extubation, possible loss of intravenous lines, or recall. Moreover, it does not pinpoint the time of onset of neurological injury and because the test is usually carried out only once during the operation it shows the neurological status only at that time.[4]

Another clinical method for spinal monitoring is the ankle clonus test: this is based on the observation that

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patients recovering from general anaesthesia will temporarily exhibit bilateral ankle clonus on clinical testing and this inability to demonstrate clonus indicates neurological damage.[5] The ankle clonus test, like the wake-up test, at their best, can only tell the surgeon that damage has already occurred, not that it is occurring.

It was not until the early 1970s that neurophysiological methods gradually replaced older clinical tests.[6–9]

This review summarises the various monitoring techniques, outlining their advantages and disadvantages primarily in relation to surgical procedures.

Somatosensory evoked potentials (SEPs)

This is the most common neurophysiological method for monitoring the intra-operative spinal functional integrity. Described 50 years ago,[10] the development of computer averaging led to clinical application in the early 1970s. SEPs are the electrophysiological responses of the nervous system to sensory stimulation. Stimulation of a mixed or sensory nerve begins a chain of electrical events culminating in the SEPs waveform. The natural volley is initiated at a distal site such as the posterior tibial nerve at the ankle and is transmitted along the nerve to the spinal cord. The incoming volley is synapsed at the dorsal horn cells of the dorsal root ganglion and transmitted through the ascending ipsilateral posterior columns of the spinal cord and synapse in the dorsal column nuclei at the cervicomedullary junction. Second-order fibres cross to the opposite side shortly after emerging and travel to the primary receiving nucleus of the thalamus via the medial lemniscus. Third-order fibres continue from thalamus to frontoparietal sensorimotor cortex. It is not known whether or not any of the activity generating SEPs in humans travels in ascending paths other than the posterior columns. However, monitoring these somatosensory pathways also provides an indirect way of monitoring adjacent motor pathways because more acute impairment affects function of many adjacent pathways, not just the posterior column.[11]

A number of studies have used SEPs in spinal cord trauma to correlate them with neurological deficit or prognosis for motor recovery. In some patients SEPs may be present despite clinically complete lesions, and progressive normalisation of the SEPs may precede clinical improvement of motor function.[12,13]

From a technical point of view, the monitoring of intra-operative SEPs requires a precise technique. This was delineated by the American Electroencephalographic Society in 1984.[14] The selection of the nerve to be stimulated is determined by the segmental level of the surgical procedure. Spinal cord surgery above the eighth cervical segment can be monitored by SEPs to median or ulnar nerve stimulation.

Because median nerve SEPs monitor large-fibre afferent input from C6 to T1, this montage was considered adequate for evaluation of intra-operative SEPs. However, some studies have shown that in patients with cervical myelopathy, median nerve SEPs show abnormalities only if there is cord compromise at the C5–C6 level or above, and less in patients in whom myelopathy extends to the C7–T1 level.[15] This finding indicates the need for monitoring of median and ulnar SEPs in cervical cord surgery. Spinal cord surgery involving levels below the eighth cervical segment requires monitoring of SEPs for stimulation of the posterior tibial nerve or common peroneal nerve.

There are at least two methods of monitoring somatosensory function during spinal cord surgery: (1) recording from the scalp surface; (2) recording from electrodes placed in the spinous process or epidural space. Intra-operatively, measurements of SEPs are obtained after the onset of anaesthesia (baseline control), intermittently throughout the operative procedure and on completion of surgery.

Outcome of different SEPs monitoring techniques has been compared among each other. Techniques commonly used in the UK or Japan are more invasive than those used in the US.[11] The various spinal cord monitoring techniques are comparable in their monitoring capability.[16] However, the optimum recording site in terms of non-invasiveness, versatility, time requirements duration, lateral discrimination, and ease of electrode placement is by cortically recorded somatosensory evoked potentials.

The minimum setting is as follows: lower extremity SEPs are obtained by stimulation of the posterior tibial nerve at the medial malleolus. Responses are recorded from C3′, C4′ and Fz locations across the somatosensory cortex, according to the International Federation 10-20 electrode system.[17] In addition to the posterior tibial nerve response, median nerve SEPs before and during surgery are recorded. This response is elicited by stimulating the nerve at the wrist and is used to determine whether degradation in the cortical SEPs to posterior tibial nerve stimulation is due to the anaesthetic.

Some advocate recording at a peripheral nerve site proximal to the stimulus and at the cervical site.[18] The peripheral response allows the examiner to determine if the stimulus has been neurologically encoded and has progressed rostrally; the cervical response is recorded because of its resistance to anaesthetic agents. An array of cortical, cervical, and peripheral sites is used to ensure that a reliable response is obtained.

False positive monitoring also occurs. A false positive reading could arise in a situation where SEPs change significantly without any apparent technical, anaesthetic-related, systemic, or surgical problem. Such false positive fluctuations usually reverse spontaneously, often within a few minutes. However it is possible that some of these false positive events represent a true positive reading, that is, a transitory physiological or functional impair-

ment of the central nervous system. With good monitoring techniques, the rate of false positive changes can be kept low.

In a study by Owen *et al*[18] SEPs were monitored during surgery for neuromuscular scoliosis. When using a single channel recording site, the false positive rate of SEPs to posterior tibial nerve stimulation was 28%. However, when a cervical recording site was added, the false positive rate for SEPs decreased to 9%.

Because of the low amplitude of the bioelectrical signal of the evoked potentials, their recording can be negatively influenced by several variables. Therefore it is important to establish and maintain throughout the operation a suitable environment for the monitoring equipment. Besides electrical interference, other inevitable physiological influences such as the patient's core and limb temperature dropping, acute hypoxia from any cause, hypotension from bleeding or medications and, especially anaesthetics, must be considered. Virtually all anaesthetic agents, besides muscle relaxants, will decrease SEPs to some degree. This effect can be more evident when using anaesthetic inhalation rather than intravenous agents.[19] Three techniques have been recommended for intra-operative SEP monitoring: narcotic/halogenate agents, narcotic/nitrous oxide, and total intravenous anaesthesia.[20]

Recording in the surgical field can give much larger responses less affected by anaesthesia and more resistant to change of the blood pressure but it is associated with the technical problems of the surgical procedure. Such recordings also generally require much technical expertise and experience for satisfactory recordings and that the surgeon be familiar with the procedure and willing to implement it.[11]

Surgical complications, particularly mechanical cord injury, can also cause acute changes in the waveform. Several animal models do suggest that the distraction and extension or straightening of the spinal cord often cause physical damage to the spinal cord. In addition, to distraction and compression of either the spinal cord or its vascular supply, surgical complications may also result from blunt injury or laceration.[21]

In general, ischaemic trauma is picked up after some delay by evoked potentials but appears to be more responsive to intervention than mechanical trauma. Animal models showed that ischaemia produces a multilevel reduction in spinal cord perfusion and a concomitant slow degradation in evoked potential response amplitude but little change in the latency of the evoked potential.[22] In contrast mechanical trauma resulted in localised ischaemia and structural damage, which is associated with a rapid degradation in the evoked potential, followed by an increase in response latency and a degradation in response amplitude.[23]

Intra-operatively the definition of a normal trace compared with normative data is not as important as the definition of a significant change from baseline. Different parameters are required for a valid SEPs interpretation: a general evaluation of the clinical condition of the patients and a qualitative and quantitative analysis of signal.[24]

Selecting the patients before the monitoring is important. If there are no potentials pre-operatively it is highly probable that none will show during monitoring intra-operatively. Pre-existing neurological deficits can substantially interfere with SEPs. Even mildly to moderately abnormal pre-operative cortical SEPs can disappear completely under anaesthesia. This is seen especially in patients with scoliosis associated with cerebral palsy, Friedreich's Ataxia, and in some patients monitored for neurosurgical disorders.[25]

If SEPs are lost during surgery, the neurophysiologist should implement the following fundamental steps to determine whether the loss of data has resulted from technical, perisurgical, or surgical variables: (a) re-perform the test and include a peripheral response to ensure that the eliciting stimulus is being neurologically encoded; (b) conduct a visual and impedance check of all recording electrodes; (c) ascertain from the anaesthesiologist whether or not changes in the level of the muscle relaxation or anaesthetic have occurred; and (d) record a response following stimulation of a different limb.

Once technical and systemic reasons for change have been considered and excluded, SEPs changes should be considered to be the result of surgical spinal cord impairment.

Brown *et al*[26] who applied SEPs monitoring on a group of 300 patients, suggested, as a significant alarm level a peak and interpeak amplitude loss of 50% of baseline. This has been confirmed by others.[27–29] Some authors suggest a 10% cut-off of the increase of latency.[27,28] However, some increase in latency has been observed as the body temperature falls and anaesthetic agents accumulate. Nevertheless, York[30] believes that a 15% increase of latency and a 50% decrease of amplitude is not indicative of post-operative neurological damage. These variations are routinely observed during surgery and the decision to alert the surgeon must also be based on the interpretation of the signal and not only on a quantitative principle. Young and Sakatani[31] also stated that simple amplitude criteria for changes are not adequate. Their criteria are based on 'duration' of changes. Changes lasting at least 10 min indicate the danger of neurological compromise.

In this way, besides the improvement of the recording, it has been possible to drastically reduce the incidence of false negatives from an incidence of 2–5% in the early 1980s[32–35] to 0.127% observed by Nuwer in a large multicentric study (year 1995) conducted on more than 50 000 patients.[36]

Motor evoked potentials (MEPs)

The primary concern of the surgeon during surgery for the correction of spinal deformity is to avoid post-

operative motor deficit. Although there is a strong correlation between preservation of SEPs and normal motor function, monitoring of SEPs primarily assess the function of the dorsal columns, not the motor system. Monitoring of the motor tracts in patients may be a more logical alternative but this technique is not yet fully developed.

The motor evoked potentials (MEPs) were first described in 1980 by Merton and Morton[37] and have subsequently been investigated with increasing vigour in recent years. MEPs are produced by synchronised, excitatory volley in corticospinal pathways. MEPs can be activated by either cortical or direct spinal cord stimulation. Both magnetic and electrical forms of stimulation have been applied. When cortical stimulation reaches anterior horn cell synapse, an excitatory postsynaptic potential is generated. If there is sufficient temporal and spatial summation of potentials, the anterior horn cells will fire and trigger a motor unit and a muscle response.

Thus responses can be monitored from both peripheral mixed nerve using subdermal needle electrodes (neurogenic motor evoked potentials) or from muscle by surface electrodes on peripheral muscles (myogenic motor evoked potentials). An alternative to stimulating the motor cortex is to stimulate the spinal cord. While Machida *et al*[38] have reported that it is possible to stimulate the spinal cord using magnetic stimulation, Konrad *et al*[39] have reported conflicting data. Consequently, MEP techniques that stimulate the spinal cord use electrical rather than magnetic stimulation techniques. With direct spinal cord stimulation, electrodes can be placed either epidurally or in adjacent spinous process. Subsequent neurogenic or myogenic responses can be recorded.

The advantages and disadvantages of magnetic *versus* electrical stimulation and the specific issues of MEPs acquisition and interpretation are dealt with in several recent reviews. In 1996 in a review of 116 cases Nagle *et al*[40] did not find any false negative readings (data remained consistent with baseline values throughout surgery, but the patient demonstrated a post-operative neurological deficit) using myogenic MEPs. In different studies Owen *et al*[21,41,42] demonstrated that the combined use of SEPs and MEPs for intra-operative monitoring provided the most comprehensive information on the status of the spinal cord. In a recent study conducted by Padberg *et al*[4] on a group of 500 patients between 1987 and 1997, there was not one false negative case. These data confirm the usefulness of associated SEPs and MEPs in preventing neurological complications.

It should be stressed that the monitoring of MEPs has never been shown to be superior to measuring SEPs, and the problems of having high energy magnetic stimulation in the operating room are not insignificant.

At present, however, MEPs techniques are still considered investigational and clinical application has not been approved by government regulatory agencies in North America.

Monitoring root function

Monitoring of electrophysiological function during intrapedicular fixation of the lumbosacral spine can be useful because the fixation technique has been associated with a significant number of post-operative radicular complications.[43] SEPs and MEPs are less specific when it is necessary to test a single nerve root function, for example during surgery for lumbosacral deformities. SEPs from the posterior tibial nerve or from the peroneal nerve relay activity from several different sensory roots. In this way the signals coming from the single affected root can be masked by those coming from the healthy ones. A case has been documented in which the intrapedicular fixation procedure that was monitored with SEPs resulted in false-negative SEPs findings.[44] These data suggest that SEPs may not be a sufficiently sensitive monitoring tool for detecting an abnormality of a single root function, and as a result, other monitoring techniques should be used.

Two neurophysiological methods have been advocated for monitoring the function of single roots: dermatomal SEPs (DSEPs) and electromyography (EMG).

DSEPs, described for the first time by Cohen in 1988,[43] are elicited by electrical stimulation of a peripheral dermatomal field; the examiner establishes the intensity level of the current required to stimulate peripheral nerve ending, but avoiding contraction of the underlying muscles. The afferent impulse runs through peripheral sensory fibres to the spinal cord at the level of the stimulated dermatomal, and then, throughout the dorsal columns to the cortex where the signal is recorded.

In a study conducted on 152 patients subjected to spinal root decompression, Cohen found that DSEPs monitoring can predict the adequacy of nerve root decompression.[45] Instead, Owen,[46] in another study conducted on 230 patients, noticed that the relationship between the improvement of DSEPs and adequacy of decompression was also affected by the duration of nerve root compression: if this is acute, it is not unusual to observe an improvement of DSEPs after surgical decompression; on the other hand, it does not appear that DESPs provide information regarding adequacy of nerve root decompression in patients with chronic root compression. In a recent study on 33 patients Tsai[47] found a DSEPs improvement on latency, amplitude and morphology, but the surgical outcome was good in only 13 patients (39.4%), concluding that improvement indicated by DSEPs improvement does not coincide with good clinical outcome.

Their application then is limited by the effect of the anaesthetic influence and by the difficulty of placing the electrode accurately on the dermatomal corre-

sponding to the root to be tested. Moreover, because DSEPs are an average record, DSEPs cannot provide instantaneous information on changing of nerve root functionality. In addition, in a prospective study of 81 lumbosacral intrapedicular procedures, it was found that predictions of post-operative outcome were dependent only on the response on completion of surgery and not on changes that occurred during surgery.[44]

The recording of electromyographic activity from the muscle controlled by the root to be tested is an alternative to DSEPs. The EMG activity can be elicited by a mechanical irritation or by an electrical stimulation.

Irritation can occur following pedicle breakout. When checking for the effects of perisurgical variables, any EMG activity present is attributed to mechanical irritation of the corresponding nerve root.[48]

Electrically elicited EMGs are administered during surgery for lumbar spine degeneration, especially if transpedicular instrumentation is used. Following placement, the pedicle screw is electrically stimulated and the EMG activity in the peripheral musculature simultaneously recorded. The rationalisation for this methodology is that an intact pedicle wall prevents the spread of the electrical stimulus from the pedicle screw to the adjacent nerve root.[49] This technique is used primarily to identify any incorrect positioning of a pedicle screw rather than for continuous monitoring of nerve roots.

Pudendal nerve monitoring

Pudendal nerve evoked potentials are used in orthopaedic surgical procedures involving fixation below the S1 level. Pudendal nerve stimulation provides information not only on lower sacral roots, but also on spinal cord function, assessing bowel, bladder and sexual dysfunction.

The stimulating electrodes are placed on the gluteal region or on the external genitalia. The recording electrodes are placed on the scalp.

In a study conducted on 154 patients, Cohen[50] found an incidence of false positive of 0.65%, concluding that pudendal nerve stimulation is a valid additional method to an evoked monitoring program.

One of the major disadvantages of this technique is that, unlike in lower extremity stimulation, the cause of total absence of response, whether due to incorrect electrode placement or neurological damage, cannot be determined until after surgery. In addition SEPs monitoring is not related to the outcome of autonomic bladder function after spinal cord injury.[51] The SEPs due to pudendal nerve stimulation include somatic nerve fibres from S2–S4, and are related to somatic nerve function (external urethral sphincter), while the vesical detrusor muscle is innervated by parasympathetic nerve fibres within the pelvic nerve.[52]

Conclusions

A wide body of data suggests that intra-operative neurophysiological monitoring is of benefit in protecting the spinal cord at risk from trauma or ischaemia during spinal surgery. There is a variety of neurophysiological procedures that can be used to monitor surgery that places the spinal cord or nerve roots at risk. In reviewing the literature pertaining to spinal cord monitoring, the majority of monitoring programs in the US utilises only mixed-nerve SEPs, not MEPs.

In 1992 the Scoliosis Research Society issued a policy statement regarding the use of neurophysiological monitoring of the spinal cord during spinal surgery. They concluded that: 'A substantial body of research has demonstrated that neurophysiological monitoring can assist in the early detection of complications and can possibly prevent post-operative morbidity in patients undergoing operation on the spine ...'. The Scoliosis Research Society considers neurophysiological monitoring a viable alternative as well as an adjunct to the use of the wake-up test during spinal surgery.[53]

Various series reporting on SEPs monitoring over two decades have established the value of such monitoring. In one large series 1168 cases were reported.[54] SEPs changes occurred in 119 patients, 32 of whom had new post-operative deficits. There were no false negatives; ie, the SEPs predicted each neurological deficit.

A large multicenter survey was conducted by Nuwer *et al*[36] to study the clinical outcome of spinal cord monitoring. This Multicenter Study of Spinal Cord Monitoring in Scoliosis Surgery surveyed members of the Scoliosis Research Society, which represents surgeons with a special interest in scoliosis. Of 173 surgeons surveyed with annual reporting of surgical complications, 153 (88%) used SEPs spinal cord monitoring. SEPs monitoring was used in 51 263 spinal surgery cases overall.

Nuwer found that the use of SEPs during surgery was influenced by several factors, including the experience of the surgeons and the monitoring personnel. For adequately experienced teams, the incidence of a major neurological deficit was 0.24%. The overall rate of neurological deficit was 50% lower among patients operated on by a surgical team that regularly used SEPs monitoring.

SEPs have also been employed in various neurosurgical procedures around the spinal cord. In addition thoracic surgeons have used SEPs during cross-clamping of the thoracic aorta to detect whether the spinal cord becomes dangerously ischaemic.[55] Moreover SEPs are sensitive to metabolic changes during surgery.

Spinal surgery for scoliosis carries some common characteristics. Frequently it involves the whole length of the spine or much of it, and mechanical forces are applied during correction thus preventing any easy and consistent recording of the exposed spinal cord. Blood

loss is often relevant and ischaemia associated with profound systemic hypotension can alter or obliterate evoked responses.[56] Last but not least, spinal surgery is time-consuming and any additional time required for monitoring is often not welcomed by the orthopaedic surgeon.

Therefore it is not surprising that SEPs monitoring of the spine is generally preferred for spinal orthopaedic surgery on scoliosis patients: (a) SEPs do not need stimulation or recording directly from the spinal cord; (b) stimulating and recording devices are at a distance from the operating table and not disturbed by the mechanical forces involved during surgery; (c) improvement in recording equipment allows consistent, reliable monitoring of very low signals; (d) the time required for technical assistance when placing the electrodes before surgery is minimal and the time required for monitoring during surgery is in the order of 1–2 min.

Today there is still no monitoring method that is able to detect all intra-operative neurological injury. However SEPs monitoring comes close to this target and has very important advantages.

In fact, in 51 263 patients studied with SEPs Nuwer *et al*[36] found an incidence of false negative (cases in which SEPs where stable, but patients had new neurological post-operative deficits) of 0.13%. Among these only 0.06% had sustained significant neurological injury. False positive (cases where SEPs changed, but patients had no new post-operative neurological deficits), were 1.51%. True positive (cases where SEPs changed when neurological damage was actually occurring) were 0.42%.

Neurological deficits (the sum of the false negative plus positive cases), were 0.55%. Persistent deficit occurred at a rate of 0.31% and transient deficit was 0.24%. The neurological deficits could be further subdivided into major (those in which the patient suffered post-operative paraparesis or paraplegia) and minor (those in which the patient suffered a radiculopathy, sensory impairment without motor loss, or other lesser degrees of neurological deficit). The rate of major deficits, if the experience of monitoring personnel was adequate, was 0.24% in the overall survey. Almost 98% of recordings were true negative; that is, no significant change in the waveform and in the neurological post-operative status. For neurophysiological monitoring to be useful, an experienced team must perform it, and both the surgeon and the anaesthetist must be willing to act on the findings. Under these circumstances, spinal cord monitoring can reduce surgical complications when correctly applied. Monitoring is however not indicated for routine lumbar spine surgery.[57]

The key message of the SRS multicenter survey is that the overall neurological deficit rate was almost 50% lower among patients operated on by surgical teams that regularly used SEPs monitoring. In addition severe neurological damage was prevented entirely by SEPs monitoring for almost one patient in every 200 undergoing surgery for scoliosis. The advantages of the preventive capability of this method contrast with its high costs. However, in the USA at least, the cost of 200 cases monitored, although great, would be substantially less than the cost of providing medical care, physical therapy and disability assistance for the lifetime of a young adult with permanent paraplegia due to surgical complications.

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