History of the development of intraoperative spinal cord monitoring

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Abstract In the early 1970s, spinal instrumentation and aggressive surgical technology came into wide use for the treatment of severe spinal deformities. This background led to the development of intraoperative spinal cord monitoring by orthopaedic spine surgeons themselves. The author's group (T.T.) and Kurokawa's group invented a technology in 1972 to utilize the spinal cord evoked potential (SCEP) after direct stimulation of the spinal cord. In the United States, Nash and his group started to use SEPs. Following these developments, the Royal National Orthopaedic Hospital group of Stanmore, UK employed spinal somatosensory evoked potential in 1983. However, all of these methods were used to monitor sensory mediated tracts in the spinal cord. The only way to monitor motor function was the Wake up test developed by Vauzelle and Stagnara. In 1980, Merton and Morton reported a technology to stimulate the brain transcranially and opened the doors for motor tract monitoring. Presently, in the operating theatre, monitoring of motor-related functions is routinely performed. We have to remember that multidisciplinary support owing to the development of hardware and, software and the evolution of anesthesiology has made this

possible. Furthermore, no single method can sufficiently cover the complex functions of the spinal cord. Multimodality combinations of the available technologies are considered necessary for practical and effective intra-operative monitoring (IOM). In this article, the most notable historic events and articles that are regarded as milestones in the development of IOM are reviewed.

Introduction

New technologies are invariably developed in response to social context and background at any given time. In this light, the 1960s can be seen as the dawn of aggressive surgical approaches to the correction of severe spinal deformities. One of these approaches was the development of instrumentation by Harrington to correct scoliotic deformity subjecting the curved spine to distraction force [1]. Although this technology was effective, it exposed the spinal cord to a risk of neurological sequelae. A morbidity and mortality report compiled by the Scoliosis Research Society in 1974 found that among 7,800 operations conducted with Harrington instrumentation, 87 patients had subsequently developed significant spinal cord problems. Seventy-four of these cases involved severe spinal cord lesions, of which around 50% were complete lesions [2]. Furthermore, aggressive wedge-osteotomy of the vertebra from an anterior approach [3] was considered to increase the likelihood of intraoperative spinal cord injury.

This background led to the development of intraoperative spinal cord monitoring (IOM). To the author's knowledge, the first surgeon to mention the need for developing this technology was Dr. Jacquelin Perry, working at Rancho

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Los Amigos Hospital. In response to her request, the author (T.T.) sought an appropriate neurophysiologic method, recognizing the feasibility of recording somatosensory cortical evoked potential (SEP). At this time, S. Goldring at Washington University was studying the effect of anaesthesia on the SEP [4]. One of the authors (T.T.) visited his institution and had a chance to see the hardware used for recording SEPs directly from the exposed cortex intraoperatively. The instruments were large, ungainly and expensive, and furthermore required the presence of several electrical engineers to connect them online to the operating theatre. The electrical instruments at that time were based on vacuum-tube and, partially, transistors, and signal-averagers of a more appropriate size were beginning to emerge in neurophysiology laboratories. Electrical amplifier performance was not as good as it is at present. These conditions hampered the introduction of intraoperative SEP measurement during orthopaedic surgery. With an eye to practical use in the operating theatre, I (T.T.) examined the feasibility of recording large-amplitude signals that travel through the spinal cord rostrally or caudally. Thereafter, I directly stimulated the spinal cord from the epidural space and picked up the signal through an electrode located in the subarachnoid space. With this electrode arrangement, the recorded evoked potentials were sufficiently large in amplitude and recordable with basic electrical hardware in the electrically noisy environment of the operating theatre. The development of this technology for recording spinal cord evoked potentials was well accepted by Japanese orthopaedic surgeons, who then conducted extensive basic and clinical studies starting in the early seventies. Surgeons who perform spine and spinal cord surgery do not consider this electrode setting particularly invasive, whereas neurologists and neurophysiologists are reluctant to accept it. In countries where neurophysiologists or technicians perform IOM, noninvasive methods, such as SEP recording, are commonly utilized. In this context, the development and utilization of technologies have been influenced by the expertise of researchers and practical users. For example, Vauzelle, who was an anaesthesiologist, developed a widely utilized wake-up test. [5]

It cannot be denied that against the historical backdrop of surgical technology development, including both electrical hardware and software, the evolution of anaesthesiology has influenced and supported the development of IOM. This multidisciplinary support has made it possible not only to protect patients against catastrophic sequelae, but also to support new, aggressive and challenging surgical procedures.

Currently, several established technologies are available to orthopaedic surgeons. Twenty years ago, we closed our article with the expectation that techniques for monitoring motor functions would be developed. Now, monitoring of

motor-related functions is performed routinely in operating theatres, although no single method can sufficiently cover the complex functions of the spinal cord. Multimodality combinations are considered necessary for practical and effective IOM. A search of the literature in this field would immediately yield about 1500 articles. However, in this review, I intend to select and present the most notable historic events and articles that can be regarded as milestones in the development of IOM.

Spinal cord evoked potentials (SCEP)

A method of spinal cord monitoring using stimulation-evoked spinal cord evoked potentials (SCEP) was developed independently in Japan by Tamaki et al. [6,7] and Kurokawa [8]. Tamaki et al. developed this method specifically for spinal cord monitoring. This technique has definite advantages with respect to SEP. The large amplitude of this potential makes it easy to record using very simple hardware and it yields real-time information useful to a surgeon because the potentials are usually large enough without averaging. As a trade-off, the electrode used to deliver stimulation to the spinal cord should be located in the epidural space, and the recording electrode in the intrathecal space. Insertion of the recording electrode into the subarachnoid space is routinely performed by inserting a Tuohy needle at the lower lumbar level [9–13].

Electrode placement can be performed safely using a specially designed flexible tube-type electrode. This electrode consists of a polyethylene tube designed for epidural anesthesia with two coils of fine platinum wire at the end, the distance between the two metal contacts being 15 mm (Fig. 1). The electrode is sufficiently flexible but adequately stiff to introduce into the subarachnoid space

Fig. 1 Flexible tube type bipolar electrode. This electrode can be introduced into the intrathecal space as well as extradural space (from reference 13 with permission)

without damaging the cauda equina and spinal cord. In the subarachnoid space, the tip of the electrode can be advanced to the level of the conus medullaris and, if necessary, to the level of the craniocervical junction. We have employed this technique in approximately 2,000 cases since 1972 without any severe complication. Epidural placement can be performed during surgery or preoperatively percutaneously.

The SCEP recorded from the vicinity of the conus medullaris after stimulating the rostral part of the spinal cord is characterized by an initial sharp spike wave followed by polyphasic waves (Fig 2). The initial spike wave has been recognized as the summation of potentials from large-diameter fibers located mainly in the posterolateral columns [9, 14] and in all quadrants including the anterior part [15,16]. The polyphasic portion mainly reflects dorsal column activity, although a proportion of these potentials are easily affected by anaesthetics, anoxia and strychnine [17]. Furthermore, Shimizu et al. [18] showed that these potentials represent the synchronized activity of interneurons and primary afferent depolarization. These observations indicate that the SCEP represents summation of activities derived from the ascending and descending tracts and neurones in the vicinity of the recording electrode. However, in a clinical setting, monitoring of this potential cannot yield sufficient information about motor-related function, as motor-related potentials are masked by sensory-related potentials, which are large in amplitude. Although SCEP has been utilized as the main technique for intraoperative spinal cord monitoring over the last 20 years or so, I have experienced false negative recordings in cases of intramedullary spinal cord tumor [19], and Koyanagi et al. reported the limitation of this potential in cases requiring parenchymal surgical manipulation [20]. More recently, we have intensively used multimodality monitoring, although SCEP measurement is still one of our standard techniques.

Fig. 2 Spinal cord evoked potential (SCEP) recorded from the level of T12 after stimulating the spinal cord at C7. The potential is consisted with initial spike wave and following polyphasic waves

Somatosensory cortical evoked potential (SEP)

Spinal cord monitoring utilizing the SEP was initially introduced by Nash and his group [21, 22]. Since then, this technology has been widely accepted because of its non-invasiveness, and is currently one of the most widely used methods for IOM in a clinical setting. The majority of orthopaedic surgeons now advocate the use of this type of evoked potential as the preferred method of monitoring. There have been numerous studies of SEP, including many reports of false negativity [23]. Dawson et al. analyzed data collected from members of the Scoliosis Research Society and European Spinal Deformity Society, and concluded: “SCEP (somatosensory cortical evoked potential) is a technique that enjoys wide spread popularity. It is a useful adjunct to the spinal surgeons’ armamentarium. It is not infallible and refinements in motor tract monitoring should decrease the incidence of false-negative cases with major neurological deficits. The wake-up test should also be considered for cases with increased risk of postoperative neurologic deficits (e.g. correction of kyphosis)” [24].

Because of its sensory-mediated character and low amplitude, solitary use of this potential is not recommended as a reliable way of protecting against intraoperative spinal cord injury. Rather, it should be regarded as one of the methods of multimodality monitoring.

Spinal somatosensory evoked potential (SSEP)

In 1972, Shimoji et al. [25] recorded spinal evoked potentials evoked by stimulation of the peripheral nerve trunks of the lower extremities, although this technology was used mainly for neurophysiological analysis of the human spinal cord. They introduced their recording electrode percutaneously because of their expertise in anaesthesiology. In 1983, the Royal National Orthopaedic Hospital in Stanmore, UK, started to use this potential for IOM [26], placing the recording electrode in the epidural space, exposing the laminae, and delivering electrical stimulation to the tibial nerve. This procedure is not difficult for orthopaedic surgeons and was accepted and used mainly in the United Kingdom. This potential reflects dorsal column activities, i.e. the sensory tract, although by switching the stimulus site, one can monitor the laterality of dorsal column lesions. Utilization of this characteristic can yield important information during posterior myelotomy to remove intramedullary spinal cord tumors.

Motor tract monitoring

One of the major ground-breaking studies related to the development of spinal cord monitoring is the manuscript

by Merton and Morton that appeared in *Science* in 1980 [27]. These authors succeeded in recording evoked muscle action potentials after stimulating the human brain motor cortex transcranially. The key to their success was high-voltage stimulation with a 0.1 μ F condenser charged to ~2,000 V delivered through electroencephalogram electrodes, although contrary to expectation, this did not work in the operating theatre. At the beginning of the 1980s, general anaesthesia with nitrous oxide and halogenated gas was the standard anaesthetic technique, and this drastically depressed motor neuron activity. This problem was resolved by the introduction of venous anaesthesia with fentanyl and propofol (AstraZeneca Ltd., Macclesfield, Cheshire, UK) by Jellinek et al. [28].

During the 1980s, neurosurgeons stimulated the surgically exposed motor cortex and recorded corticospinal evoked potentials from the spinal cord [29,30] in order to monitor spinal cord and brain function. In Japan, a group of orthopaedic surgeons stimulated the motor cortex of the brain by placing needle electrodes into the cancellous bone of the skull through a small hole drilled into the outer table of the skull [31,32].

By any means, this motor-related potential recorded from the spinal cord was employed as an indicator of the conductive ability of the spinal cord [32, 33]. Presently, this method is widely accepted as routine by many researchers and has been intensively studied by Deletis and his group [34].

Levy et al. also studied extensively the monitoring of motor tracts and developed a method for stimulating the corticospinal tract by placing electrodes on the hard palate (cathode) and skull (anode) [35]. Though this method was not widely accepted, they yielded suggestive hint about the effects of paired stimulation.

Another group of orthopaedic surgeons used stimulation of the spinal cord to evoke peripheral muscle contraction [36]. Similar to the muscle evoked potential after brain stimulation, this potential was much more difficult to record under general anaesthesia. To overcome this common problem, Inghilleri used paired cortical stimuli [37], and Taylor [38] also applied similar paired stimuli to the spinal cord. The basic concept of both techniques is effective accumulation of EPSP (excitatory post-synaptic potentiation) at the anterior horn motor neurones. To obtain more effective accumulation, this paired stimuli technique thrive in to train stimulation to the brain [39] and spinal cord [40].

The development of these neurophysiological techniques was also supported by the development of electrical hardware. A high-voltage transcranial stimulator manufactured by Digitimer Ltd. (Welwyn Garden City, UK) made the most remarkable contribution to the widespread use of motor system monitoring.

Presently, monitoring of the motor system with muscle evoked potentials (muscle MEP) elicited by short train stimulation to the brain or spinal cord is one of the routine methods for monitoring the motor tracts of the spinal cord, although the shortcomings of this method also need to be borne in mind. One of them is the very high trial-by-trial variability of muscle MEP amplitude. This makes it difficult to define criteria for a minor degree of deterioration of the motor tract as distinct from a complete loss of the response; at present. Therefore, the test must be considered a qualitative rather than a quantitative one [41]. Furthermore, the sensitivity of this potential to several kinds of insult to the spinal cord is quite high. As a result, the incidence of false positive results will increase if judgment is based purely on this potential.

To understand this characteristic of muscle MEP, Nakagawa et al. [42] carried out an animal experimental study and found that CMAP (muscle MEP), compared with other evoked potentials (conductive evoked potentials) used for multimodal spinal cord monitoring, provided the most sensitive method of monitoring possible ischemic and compressive insults to the spinal cord during surgical procedures. But the disappearance of muscle MEP does not always indicate a residual motor deficit. However, a decrease of more than 50% in the amplitude of spinal MEP (conductive motor-related potential recorded from the spinal cord: D- and I-wave) correlated well with postoperative motor deficits. Muscle MEP is useful for revealing ischemic and compressive insults to the spinal cord at an early stage, although a decrease in the amplitude of this potential does not always mean that there is a residual motor deficit. To monitor the motor pathways of the spinal cord accurately, it is necessary to employ muscle MEP concomitantly with spinal MEP (D- and I-wave) for spinal cord monitoring.

Era of multimodal spinal cord monitoring

As described above, we have at least six methods for monitoring the functions of the spinal cord intraoperatively:

1. SCEP: spinal cord evoked potential after stimulation of the spinal cord
2. SEP: somatosensory evoked potential after stimulation of a peripheral nerve
3. SSEP: spinal somatosensory evoked potential after stimulation of a peripheral nerve
4. Spinal MEP: spinal cord evoked potential after stimulation of the motor cortex (D- and I-wave)

5. Muscle MEP (brain): muscle evoked potential after stimulation of the motor cortex (brain muscle MEP)
6. Muscle MEP (spinal cord): muscle evoked potential after stimulation of the spinal cord

Utilization of these methods properly, knowing the drawbacks and advantages of each, is deemed necessary as none of these methods alone is infallible. To carry out effective and more reliable monitoring, preoperative composition of strategies related to the type of surgery, level of the spinal cord at risk, preoperative neurological status of the spinal cord and the anticipated insult to the spinal cord are all assessed for selection of the best methods for multimodality monitoring. The best array of stimulation and recording sites should be selected based upon the strategy employed. Especially, for cases requiring parenchymal manipulation, such as intramedullary spinal cord tumor, multiple techniques need to be employed (Fig. 3).

Iwasaki et al. [19] reported our experiences in 716 patients, including multi-modality monitoring, and the overall results included 652 true negative results, 12 true-positive, and 4 false negative. In 44 patients, we were unable to record any evoked potentials and their grades of spinal cord insult were worse than Frankel B. Among the 4 false negatives, 2 patients of intramedullary spinal cord tumor were treated surgically using spinal cord evoked potential alone for monitoring after direct stimulation of the spinal cord, and both of the patients recovered from anaesthesia with motor deficiency in the lower extremities. After these 2 patients outcome, we made it a rule to carry out multimodality monitoring in cases of intramedullary spinal cord tumor. Another 2 patients with false negative results developed left transient segmental motor deficit without

remarkable change in muscle MEP elicited by stimulation of the motor cortex and/or spinal cord. To understand the mechanism responsible for such results, Tsutsui et al. [43] carried out an animal experimental study and revealed that selective injury to the anterior horn of the spinal cord and spinal nerve roots does not always influence the muscle MEP. Now that these facts are established, it may be necessary to give information to surgeons and patients so that informed consent can be obtained in a practical setting.

Closing remarks

Although in reality we cannot monitor every function of the spinal cord during surgery, the technology of intra-operative monitoring has developed markedly over the last three and a half decades. This has been certainly supported by the continuous commitment of many researchers, although we also must not forget the precious dedication of large numbers of patients, without whose co-operation, none of the new techniques would have gained clinical relevance. It is true that every medical technology is developed for patients, and also for medical personnel participating in their treatment.

With regard to my own experiences as an orthopaedic spine surgeon, I have been able to rescue about 8 patents from catastrophic iatrogenic spinal cord injury during my last 15 years in practice. One of them was a 17-year-old girl with scoliotic deformity, for whom I carried out instrumentation from the posterior approach using sublamina twisted titanium wiring. When the bone grafting procedure was started, a young orthopaedic surgeon who was responsible for the monitoring noticed a change in the

Fig. 3 Multimodality monitoring in a case with intramedullary spinal cord tumor. MEP, SCEP, SSEP and CMAP after stimulating the brain (B-CMAP). Notice the variability in amplitude and pattern of B-CMAP and the polyphasic pattern of MEP. When the CUSA (ultrasonic tissue removing instrument) was used, the amplitude of B-CMAP decreased, but there was no change in the order evoked potentials. This patient woke up without neurological sequelae in upper extremities but slight degree of sensory disturbance at limited area in left lower extremity (from reference 13 with permission)

wave pattern of the spinal cord evoked potential elicited by direct stimulation of the spinal cord. As described above, this potential travels through mainly the dorsal part of the spinal cord. We could not understand what was causing the decrement, but soon afterwards, one of my assistants happened to pull out a broken sublaminar wire that had straightened to its original shape and was compressing the spinal cord posteriorly. The potential returned to the original pattern thereafter, and the patient recovered without any neurological complication. In the same sense it can be said that from my own viewpoint as a surgeon, the outcome in this case also rescued me from irreparable damage to my conscience.

In fact, reliable spinal cord monitoring encourages surgeons to carry out more difficult and challenging surgical approaches to the spine and spinal cord using the monitoring methods available. Even though current techniques are effective for monitoring the major and complex functions of the spinal cord, we must still move forward to advance our knowledge and technical skill as surgeons for the benefit of patients whose treatment and consequently their quality of life is in our hands.

Conflict of interest statement None of the authors has any potential conflict of interest.

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