Guest Editorial

Multimodal Intraoperative Neural Monitoring for Neurosurgical Spinal Operations Standard of Care—A Debate or a Foregone Conclusion and the Future Ahead

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Multimodal intraoperative neural monitoring (MIONM) has come of age.[1] From the early days in the 70s[2] with the start of somatosensory evoked potential (SSEP) recordings to monitor the sensory pathways during surgery of complex pathology in the spinal cord and nerve roots and of the bony vertebral column to the further inclusion of motor evoked potentials (MEPs) to monitor the functionally important corticospinal tract pathways and to the more recent introduction of electromyography (EMG) (free running or stimulated), the field of MIONM has truly widened phenomenally.[3]

The vascular surgeons, whose work involves the vascular supply to the spinal cord, with all its intricacies and developmental anomalies, have also been a stakeholder in the optimization of their interventions and avoidance of postoperative complications through novel techniques of near infrared spectroscopy[4] and laser flow studies, many of which are presently in an experimental stage and yet to be validated as measures to be incorporated in the clinical monitoring armamentarium in the operating theaters in the future.

Our developing knowledge of the functions of the various tracts within the spinal cord, of their vascular supply and the developmental and anatomical aberrations, the signal changes that occur during the stimulation of the structures and their dynamic changes in the OR environment, and interpretation of the same in real-time has made operations safer for the patient, the primary objective of these developments in monitoring. In addition, the surgical efficiency and understanding of the physiological/functional changes induced by the surgeon is more in the cognizance of the surgeon, as they make their careful pathway through vulnerable and precarious structures with an efficient neuronavigation monitoring "GPS" tool. Surgeons are enabled to work with reduced anxiety and increased efficiency, being facilitated to extend the benefits of their intervention without having to worry about any medicolegal consequences from any unintended adversities becoming apparent only in the postoperative period.

With more complex pathologies coming to light with phenomenal improvement and innovations in neuroimaging, surgeons globally are engaged in their cure in minimalistic interventions, lasting many exhausting hours.[5] With the potential for robotic surgery, virtual reality and augmented reality becoming everyday duties for surgeons in ever expanding indications in the future, which would certainly enable surgeons to conserve physical energy, make improved cognitive surgical judgements real-time including presurgical planning software, and avoid mental fatigue during grueling procedures in a technology rich operating environment where neural monitoring data is flowing in real-time.

In future, the neurosurgeons' OR work environment may be comparable to the cockpit of a sixth generation jet fighter (Lockheed Martin F–22 Raptor) with a flood of data from multiple inputs, providing diverse information from multiple parameters of both neural and vascular origins streaming in real-time, as the surgeon goes into more critical areas to remove pathology or restore structure and function/physiology. Advances in computing technology and data handling, with additional inputs from artificial intelligence, big data handling with the help of cloud-based platforms would become the norm rather than the novelty for surgeons to deliver optimal care for all patients.

In addition, the increasing knowledge of the role of physiology and anesthetic agents on the fluctuations and stability of the monitored parameters of MIONM has brought in contributions from specialized neuroanesthetics, who have a clear understanding of the significance of changes of temperature, perfusion/oxygenation, electrolyte alterations on the evolution of the dynamic graphs preoperatively. The role of various classes of anesthetics on the generation of

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the biological signals that are monitored has been evolving with time. A judicious balance of the anesthetic combinations (inhalational/intravenous/total intravenous anesthesia[TIVA]) during the various stages and needs of the surgical techniques (distractions/instrumentation/interventions/manipulation) spanning between four and eight hours in complex cases against the generation of interpretable and validated MIONM signals becomes a core duty of the neuroanesthetist.

With a of barrage of critical information from neuronal and vascular structural alterations flowing in preoperatively, the challenges of interpreting them and advising/informing the surgeon (the team leader/interventionalist) require dedicated/specifically trained neurologist/clinical neurophysiologists and neurophysiological technologists to become active members of the surgical team to assure the best clinical outcome for the patient postoperatively. The delays of the signal changes following surgical manipulations, the subsequent alert and the consequent reversal of surgery to observe restoration of signals, and the further progression of surgery in several similar "stops and starts" adds to the surgical/anesthetic time. This often leads to "stress" in the team environment, particularly when the monitoring signals behave unpredictably, requiring mature interpretive skills from experienced neural monitoring specialists who are limited globally in relation to an evolving and increasing demand for their services.

The SSEPs were the first to be monitored in the 1970s by Richard Brown[6] a biomedical engineer working alongside Clyde Nash, orthopaedic surgeon in Cleveland, Ohio, USA, who later went on to establish standardized protocols utilizing SSEP during spinal operations in 1988.[7] SSEPs monitor the functional integrity of the dorsal columns in a continuous manner throughout surgery with well-established recording criteria (alarms set at latency increase > 10% and signal decrease > 50% compared with baseline). The recordings can be undertaken at multiple sites around the area of interest. There is some influence of halogenated and nitrous oxide based anesthetic agents on these potentials, although SSEPs are less affected by anesthetics than MEPs. However, SSEPs result from signal averaging with consequent time delay and delays in the alert and potential irreversible injury before monitoring changes come to light. Intravenous anesthesia is ideal. The sensitivity varies between 25 to 92% and specificity between 96 to 100%. Individual nerve root function is not effectively monitored through overlap of source stimuli into the dorsal columns, where the stimulating signals confluence and recorded from scalp electrodes.

The transcranial MEP studies[8] ascertain the functional integrity of the motor pathways with transcortical electrical stimulation and offers real-time instant monitoring without any averaging requirements. In an electrically hostile OR environment and signals from surgical drills, MEPs provide robust monitorable signals compared with SSEPs. However neuromuscular blockade cannot be used during MEP monitoring, and ideally TIVA is indicated. Halogenated anesthetic agents cannot be used either. Patients with epilepsy, cardiac pacemakers, cochlear implants, raised cerebral pressures, and other contraindications limit MEP monitoring. A bite guard is mandatory to avoid tongue biting consequent to the cortical stimulation. Alerts are set with a MEP amplitude decrease > 50%–75%. Sensitivity is 75 to 100% and specificity 84 to 100%. The transcranial MEP technique monitors the entire motor system/pathway and detects potential reversible preoperative neurodeficits through spinal cord ischaemia secondary to vascular compromise and collateral development insufficiency within the segmental levels of the cord. Downsides of MEP monitoring include discontinuous monitoring of the pathways, as the stimulation is intermittent and the obvious specific and rigid anesthetic protocols.

EMG (both spontaneous free running and triggered) assesses the functional integrity of the peripheral nerves and nerve roots.[9] The spontaneous EMG provides real-time information about the root function throughout surgery, although it precludes the use of neuromuscular blocking agents. It is sensitive to temperature changes. The sensitivity reaches 100%; although with a high rate of false positive alarms, the specificity is approximately 23%. The interpretation of these waveforms is quite straightforward, although use of cautery and electrical drills near nerve roots result in false positive alarm signals for which no specific alarm criteria exist. The triggered EMG signals are particularly useful in minimally invasive spine surgery, where the anatomical landmarks are often quite challenging to visualize in the limited views. Particularly valuable with high sensitivity (99.5%) for pedicle screw insertion and medial pedicle wall breach, it is less sensitive for thoracic pedicle screws[10] than for lumbar pedicle screws. During operations on the tethered cord, the triggered EMG monitoring becomes particularly important to identify functional neuronal tissue during the process of dissection and preservation/extirpation.

When the above modalities of SSEP, MEP, and triggered and spontaneous EMG are combined dependent on the surgical location and the needs of the surgeon to monitor the specific structures that are in the operative field, a sensitivity of 100% and a specificity of 84% to 100% is reached. This however depends on the experience and training of the monitoring personnel and the appropriate monitoring planning protocol established by the surgical team prior to entry into the OR.

In numerous studies undertaken over the last five decades, the specificity, sensitivity, PPV and NPV (positive predictive value and negative predictive value) of the various modalities being studied in MIONM, either on its own or in combination in relation to the level of surgery (cervical thoracic/lumbar) and the structures being monitored (spinal cord/cauda equina/roots), have given variable results. This may be explained through study methodology errors and evolution of technology and monitoring criteria over time. Comparisons with historical studies in the nonmonitored era when Stagnara wake-up test was used, with SSEPs being added on later with current MIONM modalities and future advances in vascular monitoring, have unfortunately not shown the expected

and predicted differences/improvements, and this is likely an observational and selection/ascertainment bias. This I think has led to inertia in the uptake of MIONM as standard practice.

For further information of the significant studies reporting sensitivity, specificity, PPV and NPV of various IONM techniques, please refer to Fehlings et al[11] in and Biscevic et al[12].

Despite the above, "standard" consensus has been established in the utilization of MIONM in a wide range of conditions, namely, spinal intramedullary, tethered cord and complex scoliosis operations. Guidelines are being established where MIONM is not yet the norm. Since MIONM recordings are preserved in all cases, potential clinical negligence claims will be another aspect to consider in monitoring all interventions, in addition to establishing a safe practice and protection of the best interest of the patient.

Additional barriers in uptake of MIONM are the additional cost, the requirement of trained dedicated neurophysiologist/technicians who are mandatorily present for the entire duration of protracted surgery, the knowledge base and training and the orientation of established surgeons to this evolving and potentially intrusive intervention, increase of surgical time, availability and role of dedicated neuroanesthetists, and the absence of guidelines from professional bodies; therefore, leaving room for variations in practice in this rapidly evolving field globally.

In my personal experience of MIONM over time assisting surgical colleagues, I have witnessed the progressive incorporation of various components of MIONM and refinement of acquisition techniques and developed my personal understanding of the monitored potentials and their clinical significance. In collaboration with aortic vascular surgeon's experiences, I have realized that a better understanding of the vascular supply of the spinal cord in each patient is mandatory preoperatively, as the embryological development of the spinal vasculature leads to a wide variation in each patient, and therefore CT/MR angiography studies (in the least) need to be incorporated in preoperative planning protocol of neurosurgery. Vascular surgeons Etz et al[13] have studied spinal vascularity and development of collaterals in Yorkshire pigs. This has led to recommendations to noninvasively monitor for ischaemia of the spinal cord through techniques of near infrared spectroscopy (NIRS), laser Doppler and direct spinal cord perfusion pressure studies. These provide real-time perfusion information in intra and postoperative periods with the collateral network NIRS (cnNIRS) being noninvasive as well. These additional monitoring solutions were proposed to explain the similar occurrence of paraplegia and paraparesis following open surgery and endovascular interventions on the aorta through the issue of development of spinal vascular collaterals post cross-clamping/ligation and spinal cord perfusion pressure and spinal autoregulation factors, which were not addressed preoperatively or postoperatively previously. Addition of these extra layers of monitoring during spinal surgery will make operations safer for patients, and with increased computational power, they should not realistically add to current monitoring time.

The unexpected deterioration in the postoperative period despite normal monitoring signals at the end of surgery may be through a failure of spinal perfusion through nondevelopment of collaterals and failed spinal vascular autoregulation (particularly in hypertensive patients) in the postoperative ICU care, as studies reveal. In these patients, nonmaintenance of spinal perfusion pressure uniformly postoperatively at the individual's specific baseline spinal pressures (systemic blood pressures/mean arterial blood pressure [MABP]) preoperatively likely explains the delayed paralysis. This then calls for postoperative noninvasive spinal cord ischaemia monitoring with cnNIRS as well to ensure the best outcome for the patient. This might well explain the false negative rates of conventional neural structure monitoring only as practiced at present.

The advantages of better patient outcome and avoidance of surgical burnout and anxiety in relation to outcome in complex interventions far outweigh the barriers of MIONM. Shortage of trained and well-experienced personnel will be the main resource barrier, with alternative limited model of "surgeon directed MEP mode" adoption in the medium-/short-term being a viable alternative.

I would hope NSSI would endeavor to lead initiatives to set up intraoperative spinal monitoring guidelines and standards for Indian surgeons similar to updated ANS/BSCN guidelines for neurophysiological recordings of the spinal cord during corrective spinal deformity surgery,[14]" which I have observed evolve with time for establishment of best practice and standards of care in the UK.

The surgeon continues to be the team leader and the final decision-maker in the OR, making judicious use of the rich data constantly emanating in exponential proportion from the technological advances and gadgetry sourced to the patient for the ultimate benefit of the patient, and the efficient and comfortable working environment for the neurosurgeon.

Conflict of Interest

None declared.

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