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Monitoring the Nervous System for Anesthesiologists and Other Health Care Professionals

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Editors
Antoun Koht, MD
Department of Anesthesiology, Neurosurgical Surgery and Neurology, Northwestern University, Feinberg School of Medicine, Northwestern Memorial Hospital, Chicago, IL, USA

J. Richard Toleikis, PhD
Associate Professor
Department of Anesthesiology
Director, Intraoperative Neurophysiological Monitoring
Rush University School of Medicine
Chicago, IL, USA

Tod B. Sloan, MD, MBA, PhD
Professor
Department of Anesthesiology
University of Colorado, School of Medicine, Aurora, CO, USA

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*A few pioneer neurophysiologists,
surgeons, anesthesiologists,
and researchers from many disciplines
and countries gave birth to the field
of intraoperative neuromonitoring
over 30 years ago when together they
realized that there was a need
and a means for providing better
patient care. Their interest and efforts
resulted in numerous subsequent
international meetings, spawned the
establishment and growth of various
professional societies, and ignited
a growing interest in IOM. All of this
would not have occurred without
the contributions and support
of countless individuals who dedicated
a significant part of their professional
lives and resources to the field of IOM.
It is to these various pioneers
and individuals that we dedicate
this book.*

Foreword: Orthopedic Spine Viewpoint

We began our Case Western Reserve University (CWRU) efforts to develop a system for monitoring spinal cord function during scoliosis corrective surgery in the late 1960s. It was prompted by the risks to the spinal cord as a result of using Harrington Rods for curvature correction. From the very beginning, we approached it as a team effort. University Hospitals and CWRU had the expertise to tackle this difficult challenge, but they had to be pulled together. A young neurosurgeon by the name of Jerald *Brodkey* had some experience with a technique of summating distal peripheral nerve stimulations as they were expressed over the cortex, a process reported by Dawson in the 1950s. At the same time there was a very bright, young master's biomedical engineer, Richard *Brown* working in the CWRU biomedical engineering laboratories of Drs. Victor Frankel, MD, PhD and Al Burstein, PhD. Fortuitously, Richard's undergraduate degree was in electrical engineering and he had some free time available to work on the spinal cord monitoring project (which became his PhD thesis!).

The approach taken in the laboratory was to study the effect of graduated weights applied directly to the thoracic spinal cord of dogs for varying periods of time on the ability of the cord to transmit trains of stimuli from the distal extremities to the cortex. In the course of these studies it also became apparent that pressure, time, and blood pressure were all critical variables. Then available commercial neuromonitoring systems were used, but from the beginning Rich Brown recognized that they would not work in the highly electrically charged environment of an operating room (OR). Thus began his creation of a stand alone, portable spinal cord monitoring system capable of accurately recording the very small cortical signals generated in the hostile atmosphere of the OR. Thus “Big Blue,” as Rich would call it, came to be originally equipped with four channels, but soon expanded to eight with all data stored on tape for later analysis. “Real-time” record assessment was done by holding up a base line printout up to the light with the current record printout superimposed to visually determine latency and amplitude changes. Appropriate filtering, stimulus rates, stimulus configuration, and voltages along with Rich’s primary passion, patient safety, were all factors to be sorted out. “Warning signs” of changes in latency and amplitude were part of the equation with the 10 and 50% guidelines becoming evident even then. From the beginning, Rich’s goal was to produce a system that would prove both reliable and provide valid data – causes he championed his entire career – later holding all systems to the same fire he held his own.

Once the system had proven to be effective in the laboratory by sorting out the amounts of weight over what periods of time that correlated clinically with the presence or absence of clinical neurological deficits, it was time to take it to the OR. It was strongly suspected that the more complex anesthesia used in humans would have significant effects on the cortex and hence the records. Accordingly, the next challenge was to have an anesthesiologist who would help the team sort out this piece of the puzzle. Betty *Grundy*, MD, was the person who enthusiastically joined the team and in her own right added a great deal of knowledge to the process of making spinal cord monitoring a viable clinical tool in the OR. She also became a voice within the anesthesia profession that meticulous anesthesia protocols had to be followed for spinal cord monitoring to be effective. Along the way, Rich became quite knowledgeable regarding the various anesthetic agents used in spinal surgery to the extent that he was a frequent presenter to anesthesia grand rounds on the subject of their effects on cortical function. The final addition to the team was Marianne *Wilham*, RN, the primary orthopedic OR nurse for the spinal surgical team and a critical person in maintaining a constant process in the OR. She and Rich also became quite adept at dealing with teenage patients and parents as they went through pre-operative spinal cord monitoring testing and the next day trip to the OR for surgery.

Together this team meticulously developed protocols and systems that seemed to provide the most consistent and reliable approach to intraoperative spinal cord monitoring using Somatosensory Cortical Evoked Potentials (SSEPs). Early in this process, several significant and revealing cases were performed that were encouraging and confirmed the value of Rich Brown's "Big Blue" and the future of SSEPs. It should be noted that the "Wake-Up Test" of Stagnara came into vogue about the same time as the CWRU work, and it was adopted by the Case Team as a way to verify the findings of the intraoperative changes seen in monitoring. One early case was a patient with scoliosis and diastomatomyelia. It was elected to do the Harrington spinal corrective surgery before removing the diastomatomyelia. Each time the Harrington distraction was applied, the signals deteriorated and after removal returned. The case was aborted with no neurological deficits. The diastomatomyelia was removed and the subsequent spinal corrective surgery went forward without incidence. Other early cases included a patient with cervical spinal cord abscess in which artificially raising the blood pressure temporarily restored SSEP responses and the clinical function. There was also a case of cervical spinal cord hemangioma dissection that was performed successfully under the protective umbrella of SSEPs. Thus, these early anecdotal experiences became convincingly indicative of the potential for intraoperative spinal cord monitoring to make a great contribution to the safety of patients undergoing major corrective spinal surgery. This monitoring tool also proved to be one of the critical factors contributing to the development of more and more powerful and corrective spinal implant systems that could be applied in a safe manner.

It turns out that during the same time period, Dr. Tetsuya Tamaki and a team of Japanese researchers including an anesthesiologist, Dr. K. Shimoji, were independently working on a method for intraoperative spinal cord monitoring using spinal – spinal evoked potentials. Before long there was communication between the Case Team and Dr. Tamaki's team to the extent that a series of international spinal cord monitoring conferences were held, the first being in Cleveland, Ohio, in 1977. At this first meeting, Dr. Vernon Nickel, a highly respected orthopedic surgeon remarked to the gathering, "One day intra-operative spinal cord monitoring will be as accepted and used as the EKG." One of the key individuals in this movement to develop intraoperative spinal cord monitoring was a neurosurgeon, Dr. J. Schramm, from Germany. The list of participants continued to grow both in the United States and throughout the world in great measure because of the encouraging and engaging efforts of Rich Brown whose nature was to share his ideas and expertise freely with all who took an interest. Again this welcoming approach was grounded in Rich's passion for rigorous process, analysis, expertise, and training. Similarly he was cautious and scientifically reluctant to prematurely declare SSEPs as the "Gold Standard" for monitoring spinal cord function replacing the tried and true "Wake-Up Test". As a final note, Rich never "went commercial" with his system and expertise, but rather directed his efforts into organizing the experts in the field and establishing standards of nomenclature, processes, and technical training. He was an energetic founding member and later a president of the American Society of Neurophysiologic Monitoring to which he remained committed and focused until his untimely death.

All who have gone before would applaud this valuable book, and in particular Rich Brown, PhD, who very early on recognized the critical role that anesthesia and anesthesiologists would play in the development and practice of intraoperative spinal cord monitoring.

And the rest is history.

Cleveland, OH Clyde L. Nash, Jr., MD

Foreword: Peeling Back the Onion Skin Layers

> *"As natural selection works solely by and for the good of each being, all corporeal and mental endowments will tend to progress towards perfection."*
>
> *(Charles Darwin: The Origin of The Species, XV, 1859)*

My! How times have changed! As I write this, I am looking at a copy of an anesthetic record from June 14, 1968. Being a perpetual "pack rat," I made it a habit over the years to file cases of interest and needless to say, accumulated quite a library over the past 50 years. This case, (Fig. 1), is that of a 3-month-old baby with a diagnosis of cranial synostosis with orbital compression and the operative procedure was in three stages, the final one occurring 2 months later and involved a ventricular peritoneal shunt using the-then relatively new silastic Holter valve. In this sick and lethargic baby, local anesthetics (carbocaine) supplemented with sedation were used over the period of 3 h and 50 min. Specific monitors included a blood pressure cuff and temperature probe. For neuromonitoring, we considered ourselves "advanced" as we employed a unit that we nicknamed the "bullet" or "torpedo," since it had a cylindrical shape with a diameter of about 6 in. and a length of 1.0 foot! One end had a transparent viewplate with the tube containing a cathode ray tube and the electronics for a one-channel electrocardiogram, lead II, and another

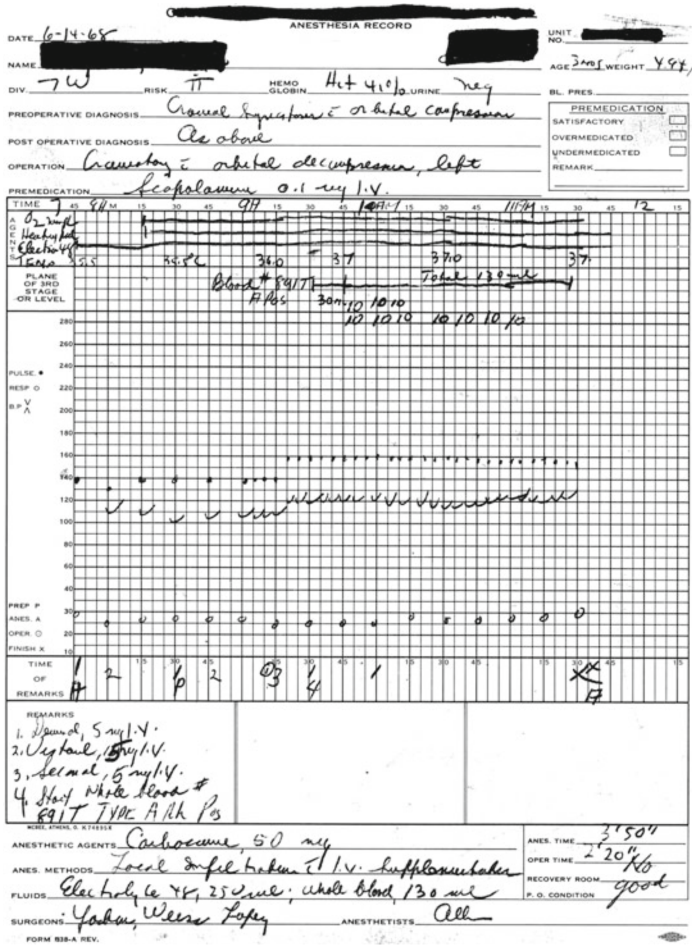

Fig. 1 A 1968 record of a pediatric case with the anesthesia provided by the author. Total monitoring included systolic blood pressure, temperature, heart rate, lead II of the EKG, and one EEG lead

single channel for an electroencephalogram lead, using a parietal presentation. Since explosive agents were in use at that time, the "bullet" had an explosion proof casing and elevated on a tripod above the 5 foot explosive level. So now we were able to visualize the EEG, EKG, and measure the heart rate with clicks triggered by the Q-T complex. If we now move 16 years to 1994, we can note the emergence of a neuromonitoring culture as demonstrated by the book edited by Peter Sebel and William Fitch, *Monitoring the Central Nervous System* [1]. There, 21 authors discussed a range of topics which are extraordinary when compared to the availability of neuromonitoring facilities in the 1960s. In this time period the horizon of neuromonitoring is expanded to not only include physiochemical topics as cerebral blood flow *and metabolism*, ICP, and EEG, but critical aspects relating to memory, recovery from anesthesia, cognitive factors, and brain death. Fast forward to today and to the wonderful effort made by the authors of the present-day book to present a sophisticated review of the great advances in neuromonitoring and its application to patient care as well as increasing our understanding of the complexities not only of the central nervous system but the incredible relationships among electrodynamic and electrochemical signaling that lead to cognitive changes which may affect modalities such as pain. Similarly, the effects of our monitoring efforts may be in themselves modified by the clinical medium of anesthesia and cause a shift in the paradigm, which in a sense involves monitoring the monitors and helps to eliminate false assumptions [2, 3]. The expertise and experience of the authors contribute greatly to a sense of true security that these methodologies have been tested by those knowledgeable in their field. Further cementing the link between development and application are the hard-nosed Case-Based Presentations of practitioners often highlighting those on both sides of the procedure table. This type of hegemony is critical for carrying out many of these procedures. This book has important source material even for those not directly connected with the many procedures listed in the Table of Contents, for many of the authors are not only capable as practitioners, but have had a primary role in developing the many neuromonitoring techniques listed.

Before terminating this Preface, I must take a moment to pay homage to one, who, in many ways is regarded as the "Mother" of neuromonitoring in the anesthesia and neurological community, namely, Betty Grundy, MD. I have known Betty for more than 40 years and can attest to how hard she has worked to bring electrophysiological monitoring into the operating room and clinical arena as well as educating a whole host of superb clinicians and those doing research in this area.

Birmingham, USA Maurice S. Albin, MD., M.Sc (Anes.)

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Foreword: Neurosurgeon's viewpoint

I am honored to have been invited to provide a foreword to this important volume. As a practicing cerebrovascular surgeon, I have a unique perspective on the field of neuromonitoring as I function somewhat as a "consumer" of these very valuable resources. Vascular surgeons are charged with exposing the brain, retracting brain tissue, reconstructing complex vascular anatomy, temporarily interrupting cerebral blood flow, and performing complex revascularizations. Not infrequently our target organ is already diseased and dysautoregulated at the time we expose it. While we have marvelous technologies to allow us to perform computerized image guidance, highly magnified 3-dimensional views, and microsurgical instrumentation that allows extraordinary things to be done, we perform this invasive maneuvers blinded as to how the brain is tolerating these actions. Neuromonitoring, when performed by skilled technologists and physicians with high expertise in the interpretation of data provide the surgeon with actionable information that can prove lifesaving.

From my perspective, one of the most interesting aspects of contemporary neuromonitoring lies in the domain of systems-based practice and communication. The surgeon often feels like a pilot of an aircraft in which he or she has certain control capabilities but because the door is closed behind the pilot, he or she has essentially no knowledge of what is happening in the rest of the aircraft. It is critical that in our surgical environments the "door" remains open and that the key human elements have professional confidence in each other and communicate openly. At the start of the procedure, everyone responsible including the physicians, technologists, and nurses must understand the nature of the planned procedure, important details about the patient, the general phases of the operation expected, and when the critical moments will be occurring. As each stage of the procedure unfolds, the entire team must be aware of those transitions. When an unexpected anomaly develops, a rapid assessment of its significance must be performed followed by direct communication with the surgeon. A timely but deliberate discussion of the options to be considered and which one to be pursued assures the optimal environment for the patient's successful outcome.

It cannot be over emphasized that successful surgical neuromonitoring requires a coordinated team effort. The critical elements obviously include in-depth knowledge of the principles of neuromonitoring and technical proficiency. Yet, without a full understanding of the patient's physiologic state prior to surgery and the unique aspects of patient positioning, abnormal data may be misinterpreted. The principles of the planned surgical procedure must be understood by all team members and constant communication must occur among the key participants to assure that proper perspective of the environment is obtained prior to the announcement of an abnormal finding.

Clearly this book will be a significant benefit to surgeons, technologists, neurophysiologists, anesthesiologists, and neurologists. The information contained in these chapters will empower the surgical team members with the knowledge needed to interpret unexpected changes and to react quickly and appropriately. This book will be an important reference for all members of these teams and hopefully enhance our ability to provide safe procedures with optimal outcomes.

Chicago, IL

H. Hunt Batjer, MD., F.A.C.S
Professor and Chair
Deportment of Neurological Surgery
Northwestern University Feinberg
School of Medicine

Preface

Intraoperative monitoring of the nervous system (IOM) has become common place in orthopedics, neurosurgery, otologic surgery, vascular surgery, and other procedures. In addition to the improvement in patient outcome which has been observed in several circumstances, the monitoring has been incorporated into the management of surgical procedures where the nervous system is at risk. The use is being fueled by the understanding that functional knowledge of the nervous system is an important partner to structural knowledge and both contribute to the quality of care and patient safety.

IOM is more than just a tool like fluoroscopy, intraoperative MRI, or CT scanning which gives a structural view of the patient's anatomy. IOM provides a means for assessing the nervous system function and determining how the surgical, anesthetic, and physiological environment are impacting this function. Pamela Prior expressed it well in 1985 when she said "routine clinical monitoring of ECG, arterial pressure and blood-gas tensions only indicates the adequacy of factors supporting brain function. The EEG and evoked potentials are more valuable because they can monitor continuously the end result at a neuronal functional level."[1] This "window to the nervous system" allows all of us to bring our own contributions to help our patients have the best possible outcomes. The prompt diagnosis of circumstances unfavorable to the nervous system will enable timely adjustment of the pharmacologic and physiologic environment to augment surgical decision.

IOM has evolved in the last 30 years from the lonely somatosensory evoked potentials (SSEP) modality that was used during spine surgery to now include; MEPs, both free running and triggered EMG, D waves, the H reflex, and other monitoring modalities. This expansion was not restricted to spine surgery but extended to other surgeries including those of the head and neck. The addition of IOM multimodalities allowed a more comprehensive assessment of the nervous system while adding restraint on the anesthetic technique. The optimal anesthetics for one modality is often not the same as that for others, thus a very delicate anesthetic balance is needed and complete cooperation between the IOM team and the anesthesiologist is invaluable.

This team effort is the key to the best patient outcome. Clearly the monitoring is helpful to the surgeon, but it is equally valuable to the anesthesiologist. In that respect, IOM allows the anesthesiologist to see the impact of the anesthetic and physiologic management on the functional integrity of the nervous system. For example, there is a growing appreciation that a blood pressure which might be appropriate for one patient may not be adequate for another. Further complicating factors are the aging patients with increased comorbidities and the more complex surgical procedures with increasing neurological trespass. IOM can help the anesthesiologist insure that the environment of the nervous system is optimal for the individual and to adjust the patient's physiology as needed when the surgical procedure places an additional stress on the nervous system.

This interplay of anesthesia, physiology, and surgery is what makes IOM different from the use of these techniques for diagnostic assessment of pathology in the nervous system. The situation is dynamic with a constantly shifting equilibrium of the effects of the procedure, the drugs given, and the physiological milieu. This is why IOM, like monitoring of blood pressure, heart rate, oxygenation, etc., must be done constantly to identify changes that allow rapid correction while adverse neurological circumstances are still reversible. Some of that reversibility will be contained in the surgical maneuvers, but changes in the management of the anesthesia, physiology, and positioning of the patient can mitigate some of the adverse effects of the procedure.

Well recognized by anesthesiologists, each patient is different, not only in their pathology and comorbidities, but also in how they will react to anesthesia and the surgical procedure. Each patient therefore presents a different problem. An injury could develop and progress without the surgeon's, proceduralist's, or anesthesiologist's knowledge. This is where IOM can become valuable to identify functional changes in the nervous system which will not be observed in structural studies or reflected in other means of traditional monitoring.

To make the team effort most effective, each member of the team needs to understand each other's roles. Like an interlocking crossword puzzle, the interface of each other's contribution is made stronger when each one knows about the other and the more effective the team becomes. This book is designed to help all members of the operative team to better understand what each member of the team is doing. It is not designed to provide technical details since there are many excellent papers and books on that subject. Rather we have sought to allow everyone an opportunity to gain insights into each of the operative components.

Many of the early applications of IOM were developed in the 1970s by surgeons, neurophysiologists, anesthesiologists, and other researchers both in the USA and Japan, as they recognized that the development of aggressive treatment programs carried a high risk of secondary spinal cord damage and that there was a need to develop methodologies for defining and evaluating spinal cord function. Among these were Clyde Nash, MD, and Richard Brown, PhD, who pioneered the use of SSEPs during Harrington distraction of the spine in patients with scoliosis [2]. This advance from the intraoperative wake-up test of Vauzelle and Stagnara would become increasingly important as procedures presented multiple possible injurious steps [3]. In patients with many significant comorbidities, a one-time clinical assessment which was used in healthy young patients with scoliosis is not applicable. The pioneers of IOM not only developed the techniques for monitoring, but they designed and built equipment to meet the specific challenges present in the operating room that were not encountered in the diagnostic laboratory. They also recognized the importance of the team effort and that such things as blood pressure management during distraction of the spine was essential for overcoming the effects of the procedure [2]. With an awareness that others were beginning to address the need for monitoring spinal cord function, Clyde Nash and Jerald Brodkey invited participants from throughout the world and hosted the first two symposia on spinal cord monitoring which were held in Cleveland in September 1977 and St. Louis in January 1979. These were followed by a series of International Symposia on spinal cord monitoring, the first of which was held in Tokyo, Japan, in 1981 and was hosted by Dr. Tetsuya Tamaki. Three years later, Dr. Johannes Schramm hosted the Second

International Symposium held in Erlangan, Germany (1984). The Third and Fourth Symposia were later held in Annapolis, Maryland (in 1986) and Niigata, Japan (in 1989), and were hosted by Drs. Thomas Ducker and Richard Brown and by Dr. Koki Shimoji, respectively. Special thanks to these early pioneers who recognized the importance of this new technology and worked to strengthen it and expand its usage. Subsequent to the International Symposia came the formation of the American Society of Neurophysiologic Monitoring (ASNM) in 1989, and also the advent of the International Symposia on Intraoperative Neurophysiological Monitoring in Neurosurgery held in New York and hosted by Drs. Vedran Deletis and Fred Epstein (1998–2006). From these latter symposia came the formation of the International Society of Intraoperative Neurophysiology (ISIN) in 2006.

IOM has evolved from the early days. Some of the techniques currently used are refinements of the early techniques while others are completely new. The monitoring professionals have recognized that the changes in neurophysiology that result from anesthesia and surgery are different from those seen in the laboratory which makes diagnostic approaches less applicable. Further, IOM must be done with constant, rapid updates to provide timely information about the state of the nervous system. This evolution in techniques has been accompanied with the development of a new field of intraoperative neurophysiology with professionals who have dedicated their career to IOM. The backgrounds of these individuals are as diverse as the techniques currently being employed. Some come from the logical pioneering fields of orthopedic surgery, neurosurgery, neurology, and anesthesiology. But a whole new field of intraoperative neurophysiology has developed with individuals bringing to bear their knowledge of intraoperative neurophysiology with the many allied medical fields to provide focused IOM care. These individuals have been responsible for many developments in the field and are key to the current utilization of monitoring for providing excellent patient care.

Many of the early developments of IOM can also be attributed to anesthesiologists. Recently, Tamaki (orthopedic surgeon) wrote an article about the history of EP monitoring and credited Shimoji (anesthesiologist) with introducing epidural evoked potential monitoring in 1971 [4]. Betty Grundy, MD, as an anesthesiologist involved in the early applications of IOM recognized this in 1982 when she wrote about the application of auditory evoked potentials in surgery on the brainstem in the *Journal of Neurosurgery* “we wanted early indication of deteriorating function so that we could intervene to prevent permanent injury. We therefore selected an approach similar to that used for intraoperative monitoring of other physiological parameters such as heart rate or arterial blood pressure, attempting to correct undesirable trends as soon as these could be identified with certainty" [5].

Dr. Grundy went on to bring IOM into anesthesiology; her landmark article in Anesthesiology in 1983 was a call for anesthesiologists to take an active role in the team. She noted that "the hope is that deteriorating neurologic function will be detected early so that the surgeon and/or anesthesiologist can intervene to optimize function and minimize the possibility of permanent damage to the nervous system" [6]. Dr. Grundy was to further stress that role when she wrote in 1984 "the anesthesiologist has important responsibilities in facilitating the electrophysiological monitoring. A multiplicity of factors under their control of the anesthesiologist can alter evoked potentials" [7]. Her early experience noted the interaction of anesthesia, physiology, and the nervous system which supported her recommendations for anesthetic and physiological management; without IOM many unfavorable interactions would have gone unrecognized. These observations are still echoed today.

As IOM techniques and applications have evolved, some advancements have come from anesthesiologists. In particular, the anesthetic techniques and physiological management that supports IOM, and which have been refined from observations made by IOM, have also improved patient care. Many anesthesiologists remain actively involved in IOM and are contributors to this book.

As the field of IOM has developed, the cadre of IOM professionals that has emerged to provide the best neurophysiological monitoring has been a distraction from the integral role of anesthesiologists in the IOM team. As such, this book is devoted to restoring that role by focusing on the knowledge and experience gained by anesthesiologists and professionals who are part of the IOM team. Our goal is to facilitate the most effective team effort by expanding the interface of knowledge between the surgical, anesthesiological, and neurophysiological members.

The first section describes the different techniques used in monitoring. The goal is to provide insight into the anatomy, physiology, and techniques so that the information provided by their use can be placed in the context of the surgical, anesthetic, and physiological management.

The second section seeks to provide basic aspects of anesthetic management. Not only will this be helpful to anesthesia providers seeking to refine their choice of medications, but it also will be helpful to practitioners in other specialties to understand the challenges inherent in the anesthetic management. Some anesthesiologists are concerned about anesthesia without muscle relaxants while other members of the team may be concerned about any use of muscle relaxants. The contributions of the authors will be helpful to reassure both that it is possible to meet this need and successfully obtain optimal signals which will enable the team to effectively monitor the patients and for the surgeon to make the best decision.

Finally, the book provides case examples of specific types of procedures where IOM has become a routine part of the management. In each case the chapter provides an overview of the anatomy, neural physiology, and pathology which is central to the procedure. Understanding this allows each member of the team to understand how the procedure, anesthesia, physiology, and IOM come to bear on the risks of the procedure and outcome. In each case, the authors have also presented some examples of typical IOM changes in these cases. This allows discussion of the differential diagnosis of the effects which could cause these changes. In that respect, the emphasis has been on non-surgical effects to allow better insight into the ways that the management of anesthesia, positioning, and physiology can contribute to improved outcome.

We have assembled a prestigious group of contributors who are all actively involved in the team efforts of IOM during various surgical procedures. Each has contributed their knowledge and experience to improve all of our effectiveness in these procedures. Hopefully, by sharing our knowledge and experience we can make the fabric of our team efforts stronger and provide the best possible care of our patients.

Chicago, IL — Antoun Koht
Aurora, CO — Tod B.Sloan
Chicago, IL — J. Richard Toleikis

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Contents