Principles of Neurophysiological Assessment, Mapping, and Monitoring

Scott Francis Davis
Alan David Kaye
Editors

Second Edition

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Editors
Scott Francis Davis
Department of Anesthesiology
Louisiana State University School of Medicine
Tulane University School of Medicine
New Orleans, LA
USA

Alan David Kaye
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences
LSU School of Medicine
Shreveport, LA
USA

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I would like to thank my colleagues in the field of IOM, whose passion and commitment to patient care have made this work possible. To Dr. Alan David Kaye, who has mentored me as an editor and professor; his wisdom and tireless work ethic are beyond compare. To Nick Luekenga and all of my colleagues at Neuromonitoring Associates, who provide me with support and friendship and who themselves are among the best advocates for patient care in the field.

Most of all, I am grateful to my wife, Robin, and my wonderful kids, Georgia Rose, RJ, Scottie, and Graham. They are God's most precious gift. Last, but not least, I still dedicate all I do – ad majorem Dei gloriam!

Scott Francis Davis

To my wife, Dr. Kim Kaye, and my children, Aaron and Rachel Kaye, for being the best family a man could ask for in his life. To my brother, Dr. Adam Kaye, Pharm D, for being the best "budder" in the world. To all my teachers and colleagues at the University of Arizona in Tucson, Ochsner Clinic in New Orleans, Massachusetts General Hospital/Harvard School of Medicine in Boston, Tulane University School of Medicine in New Orleans, Texas Tech University Health Sciences Center in Lubbock, and LSU School of Medicine in New Orleans.

Alan David Kaye

Foreword

In the constantly evolving realm of fundamental, translational, and clinical medical sciences, it is imperative that cutting-edge knowledge be synthetized and transmitted clearly and accurately to healthcare providers. This book deals with intraoperative monitoring, a field that has evolved rapidly in the last few decades. Intraoperative neurophysiologic monitoring has become an important area because it provides functional information in real time during surgery, thus benefiting patients and serving as an essential guideline for surgeons in the prevention of neurological damage. Therefore, multidisciplinary knowledge spanning neurophysiology, anesthesiology, neurology, and neurosurgery is enriching this field, owing to the creation of a two-way channel of communication, from the lab bench to the clinic and from the patient to the lab. This includes monitoring of the electrical activity of the nervous system (auditory and somatosensory evoked potentials and EEG).

That is where this book comes in: *Principles of Neurophysiological Assessment, Mapping, and Monitoring, Second Edition*. Based on their combined knowledge and experience in intraoperative neurophysiologic monitoring and neurophysiology in neurosurgery, Drs. Alan David Kaye and Scott Francis Davis have assembled a textbook that is a well-integrated blend of contemporary fundamental and clinical sciences aimed at clinicians who monitor the function of the nervous system during surgery. Dr. Kaye is an outstanding leader of the academic program in anesthesiology at the Louisiana State University Health Sciences Center (LSUHSC), New Orleans, and Dr. Davis has distinguished himself, due to his talent, drive, and motivation, since he was a graduate student in the LSUHSC Interdisciplinary Graduate Program.

While there are advanced texts leveled at neurophysiologists, surgeons, and residents alike, there are few that expound upon the basics of intraoperative neurophysiologic monitoring in such a way that those just entering the study can understand the underlying principles of this field. At the same time, the way that the materials are presented here also will be very useful to experienced specialists. The contributors to this book provide the brick and mortar that lay the foundations of neurophysiologic monitoring, which will benefit new technologists all the way to neurophysiologists and neurosurgeons. The second edition offers a number of improvements that I know you will enjoy!

Not unlike Wilder Penfield, who pioneered seminal brain mapping studies, this book seeks to provide a comprehensive guide to students just beginning their journey and experts searching for an excellent reference to other aspects of intraoperative neurophysiologic monitoring and neurophysiology in neurosurgery.

Nicolas G. Bazan, MD, PhD
Boyd Professor; Ernest C. and Yvette C. Villere
Chair for Retinal Degenerations
Professor of Biochemistry and Molecular Biology,
Ophthalmology, and Neurology
Director, Neuroscience Center of Excellence, School of Medicine
LSU Health New Orleans, New Orleans, LA, USA

Foreign Adjunct Professor of Neuroscience
Karolinska Institutet, Stockholm, Sweden

Preface

The second edition of *Principles of Neurophysiological Assessment, Mapping, and Monitoring* is intended to provide a timely update to the first edition text and continue the mission of educating new neurotechnologists, residents, and physicians in the field of intraoperative monitoring. New chapters on pediatric monitoring and spinal cord mapping and monitoring offer the reader a wealth of knowledge on two scarcely covered topics in IOM. The second edition also contains review questions at the end of many chapters that will help focus the instructor and student on the critical information in each chapter. It is our hope that this text will continue to provide a robust standard introductory curriculum to new practitioners in the exciting and growing field of intraoperative neurophysiological monitoring.

New Orleans, LA, USA

Scott Francis Davis
Alan David Kaye

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Contributors

Best Anyama, MD Louisiana State University School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Jeremy Andrew Bamford, PhD, CNIM Department of Anesthesiology, Louisiana State, University Health Sciences Center, New Orleans, LA, USA

Nicolas G. Bazan, MD, PhD Ernest C. and Yvette C. Villere Chair for Retinal Degenerations, Neuroscience Center of Excellence, School of Medicine, LSU Health New Orleans, New Orleans, LA, USA

Karolinska Institutet, Stockholm, Sweden

Ramsin Benyamin, MD Millennium Pain Center, Bloomington, IL, USA

Department of Surgery, College of Medicine, University of Illinois, Urbana-Champaign, Urbana, IL, USA

Aaron J. Beverwyk, MS, CNIM Neuromonitoring Associates, Las Vegas, NV, USA

Denise A. Birkholz, PhD, CNIM Neuromonitoring Associates, LLC, Las Vegas, NV, USA

David L. Cedeno, PhD Millennium Pain Center, Basic Science Research, Bloomington, IL, USA

Elyse M. Cornett, PhD LSU Health Shreveport, Department of Anesthesiology, Shreveport, LA, USA

Pedro Coutin-Churchman, MD, PhD Ronald Reagan UCLA Medical Center, Department of Clinical Neurophysiology, Los Angeles, CA, USA

Scott Francis Davis, PhD, MBA, CNIM Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

Vedran Deletis, MD, PhD Department of Neurosurgery, University Hospital, Dubrava, Zagreb, Croatia

Albert Einstein College of Medicine, New York, NY, USA

Ken P. Ehrhardt Jr., MD Louisiana State University School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Joseph H. Feinberg, MD, MS Hospital for Special Surgery, Department of Physiatry, New York, NY, USA

Charles Fox, MD Department of Anesthesiology, Louisiana State, University Health Sciences Center Shreveport, Shreveport, LA, USA

Jay S. Grider, DO, PhD, MBA University of Kentucky Medical Center, Department of Anesthesiology, Lexington, KY, USA

Bharat Guthikonda, MD LSU Health Sciences Center, Department of Neurosurgery, Shreveport, LA, USA

Mark R. Jones, MD Harvard Medical School, Beth Israel Deaconess Medical Center, Department of Anesthesia, Critical Care and Pain Medicine, Boston, MA, USA

Aaron J. Kaye Department of Anesthesiology, Medical University of South Carolina, Charleston, SC, USA

Alan David Kaye, MD, PhD Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

Jonathan Lissauer, MD Department of Anesthesiology, School of Medicine, Louisiana State University Health Sciences Center, New Orleans, LA, USA

Kenneth Mancuso, MD, MPH University Medical Center New Orleans, Department of Anesthesiology, New Orleans, LA, USA

Justin E. McKone, MS Lousiana State University School of Medicine, New Orleans, LA, USA

Mark W. Motejunas, MD Louisiana State University School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Jonathan A. Norton, PhD Royal University Hospital, Department of Neurosurgery, Saskatoon, SK, Canada

Matthew B. Novitch, BS University of Washington, Department of Anesthesiology, Seattle, WA, USA

Marc R. Nuwer, MD, PhD UCLA School of Medicine, Department of Neurology, Los Angeles, CA, USA

Christopher J. Pace, PhD, CNIM Neuro Alert and Center for Electroneurodiagnostics, White Plains, NY, USA

Amit Prabhakar, MD, MS Emory University School of Medicine, Department of Anesthesiology, Division of Critical Care, Atlanta, GA, USA

Kristin Krasowski Reed, DPT, CNIM NeuroLogic, Greenwood Village, CO, USA

Jordan S. Renschler, BS Louisiana State University School of Medicine, Departments of Anesthesiology and Pharmacology, New Orleans, LA, USA

J. Arthur Saus, MD, FASA Ochsner LSU Health, Department of Anesthesiology, Shreveport, LA, USA

Lara M. Schrader, MD UCLA School of Medicine, Department of Neurology, Los Angeles, CA, USA

Jay L. Shils, PhD Rush University Medical Center, Chicago, IL, USA

Rush University, Department of Anesthesiology, Chicago, IL, USA

Harish Siddaiah, MD Ochsner LSU Health, Department of Anesthesiology, Shreveport, LA, USA

Tod Sloan, MD, MBA, PhD University of Colorado, Department of Anesthesiology, Aurora, CO, USA

Lucy R. Sullivan, REEGT, CLTM ASET, Goodson, MO, USA

Ricardo Vallejo, MD, PhD Millennium Pain Center, Bloomington, IL, USA

1 Introduction to the Operating Room

Kristin Krasowski Reed and Scott Francis Davis

Introduction

The IOM clinician is part of a patient care team that consists of the surgeon, nurses, technologists, and anesthesiologists. You will recognize that each team member has a specific role to fulfill in order to provide the best care for the patient. As an IOM clinician, you will spend the majority of your working hours inside a hospital operating room (OR). The OR is a unique environment that may take some time getting used to. You will encounter different types of equipment as well as rules for navigating the space and interacting with other team members. This chapter will introduce you to the operating room along with the equipment and personnel you will encounter there.

Going to the Hospital

Going to a new hospital can be a daunting task for even the seasoned neuromonitoring clinician. There are many hurdles that you must jump before you even meet the patient, from finding the appropriate place to park to navigating your way to the OR suite. Luckily, most hospitals have a similar layout.

Your journey begins with actually finding the hospital. You may often find yourself driving to a hospital in a new city in the early morning darkness. As you get closer, there are road signs that will help you to navigate the rest of the way in. These road signs are blue squares with a single white H (Fig. 1.1). Of course, you may let your GPS be your guide. Once you have found the hospital, you have to find an appropriate place to park. Dedicated patient or employee parking is often not permissible since the neuromonitoring

Fig. 1.1 An example of a road sign directing traffic toward the nearest hospital

K. K. Reed
NeuroLogic, Greenwood Village, CO, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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service is considered a contracted vendor and not actual employees of the hospital. If you find dedicated visitor sections of the parking, that would be the best choice.

If this is your first trip to a new hospital, be familiar with the entry requirements for the facility you are visiting. For example, do you have to sign in at a security desk? Does the hospital use a third-party vendor credentialing service that has a self-service kiosk for you to obtain a badge? Maybe you need to visit the hospital biomed department to have your machine checked before bringing it to the OR. When in doubt, ask for assistance from hospital volunteers or security personnel. Once you have obtained a badge and had your machine checked (if required), you are on the lookout for the operating room. Begin by following signs to preoperative, postoperative, or surgery.

The OR suite has multiple areas that you will learn to navigate, including the individual operating rooms. Most operating suites have a similar layout (Fig. 1.2). Among the areas you will encounter are changing rooms (usually connected to a staff lounge), a control desk (also called the front desk or bridge), offices, a substerile corridor connecting the individual operating rooms, and pre- and postoperative holding areas. It is important to become familiar with which areas are restricted to personnel in scrub attire and which are not. These areas are often indicated with either a sign or a strip of red tape on the floor.

When first entering the OR suite, the first room you may come across is the locker room. Inside the locker room, scrub pants and tops will be available. You should arrive in professional clothing and change into hospital-provided scrubs upon entering the operating suite. Sometimes you will find empty lockers for visitor use. If you are concerned about the security of your valuables, you may wish to carry your own padlock. There is often an exit door into the OR corridor once you are dressed out in scrubs. Either inside or just outside the locker room will be bins with scrub hats and protective shoe covers. In the OR corridors, scrubs, hats, and shoe coverings are required; however, masks are not needed until entering the substerile corridor or an OR that has open sterile equipment or a surgical procedure in progress.

Once dressed out, the first stop you should make is to the control desk to look at the board. The board may be either a traditional whiteboard or more sophisticated panel of LCD monitors. No matter if simple or sophisticated, the board contains all of the information on surgical procedures being performed in the operating suite that day. It will show information on the scheduled start time, the room number, the procedure, and the surgeon. The board may indicate the current status of the procedure (in progress, delayed, etc.). You should always check the information on the board against the information you had

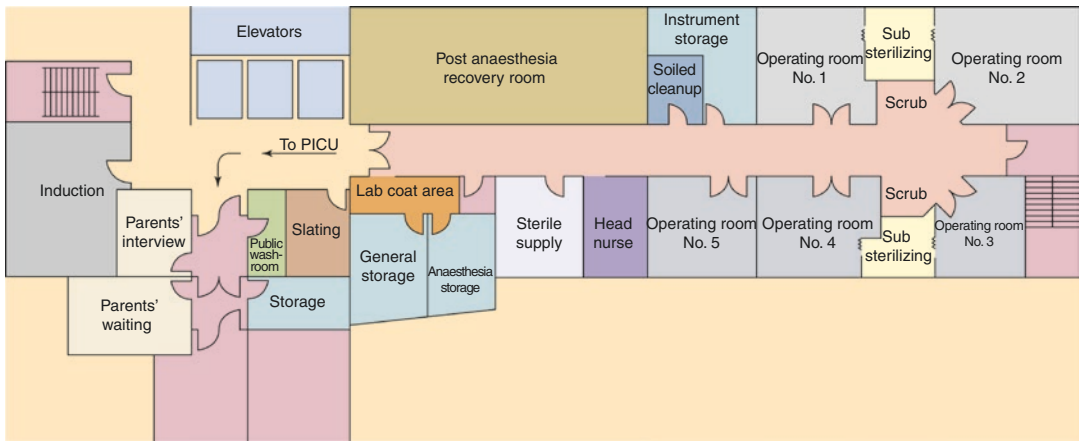

Fig. 1.2 Floor plan showing the layout of a typical operating suite

prior to coming to the hospital. It is common to discover that the cervical fusion you thought you were monitoring is really a lumbar fusion or even that your case has canceled or been delayed.

Now you are ready to go back to the room. If there is a substerile corridor, you should enter the room from here. This is to limit the entry of air from the nonsterile corridors, which are generally only used to bring the patient into the room. If possible, get a cart and set your machine up in the substerile area and bring it into the OR, leaving your machine case in the corridor. Remember your machine case has been sitting in your house and car as well as rolled through the parking lot. It might have dirt, pet dander, etc., on it. No one wants your cat's hair contaminating the room. If you are the first member of the OR team entering the OR, you do not necessarily have to have a mask on as nothing in the room is sterile yet. Once the equipment to be used during the surgery has been opened, all members of the team must have their masks on. This equipment is easily recognizable by the blue sterile packaging it comes in. Remember: in the OR blue or clear plastic equals sterile, which means that masks should be on and covering your face.

The individual operating rooms are well lit, slightly cooled, and humidity controlled to decrease the spread of infection. They have specialized air handlers that filter air and keep the pressure slightly raised. The positive pressure environment serves to push air out of the room when the door is opened in order to keep germs and insects out of the room.

Once inside the operating room, you will see many pieces of equipment. The room is set up strategically to maximize efficiency and minimize the chance for infection. For example, the sterile table of instruments will be located on the opposite side of the room from the doorway. The operating table (sometimes called the bed) is usually in the middle of the room, and the anesthesia machine is located at the head of the operating table. Microscopes, neural navigation, and X-ray equipment (C-arms and O-arms) remain against the walls. They need to be brought in close to the bed. Remember that these larger items will be covered with a sterile clear plastic drape before being used. It is permissible to touch these items before they are draped but not after.

When you first enter the OR, you should identify an appropriate place to set up and monitor the case. Always introduce yourself to the circulating nurse and politely ask where you should set up. Generally it is best to set up adjacent to the anesthesia machine. This location gives you good access to the patient as well as to the anesthesiologist or CRNA. By monitoring from this location, you avoid having to get up from your station to gather anesthesia information.

Pre- and Postoperative Areas

Prior to being brought back to the operating room, the patient is held in a pre-op staging area. The period of time before the patient is brought to the room is a hectic one with all members of the team trying to gain access to the patient before the patient is anesthetized. It is during this time that consents for treatment (including monitoring) and past medical and surgical histories are obtained. The neuromonitoring clinician uses this opportunity to confirm the surgical procedure and levels as well as to identify any preexisting pathologies that may affect the monitoring data. At the conclusion of the procedure, the patient is brought to the postoperative area, also called the recovery room. It is here that the monitoring clinician will assess the patient's postoperative neurological status.

The Surgical Team

Surgery should be considered a team sport. There is a unique cultural undercurrent that is present in the operating room that you will find no matter what part of the country you are working in. The surgeon is first and foremost the team captain. All members of the team must carry out their responsibilities with attention to the wishes of the surgeon. To help ensure consistency, each surgeon has preference cards that are reviewed by

the surgical staff prior to the start of the procedure. Preference cards have information such as how the surgeon likes the patient positioned and prepped along with information on types of instruments that should be available. This information is useful to you when planning your IOM setup. You should create your own surgeon preference cards specific to IOM that can be shared with colleagues that may monitor cases with the same surgeon.

If the surgeon is the team captain, the circulating nurse is the team manager. The role of the circulating nurse is to make sure the procedure runs safely and smoothly. The circulating nurse is in charge of how the room is to be set up (including on where the neuromonitoring team will do their job), prepping the patient, and making sure that all of the equipment, instruments, and supplies are readily available during the procedure. The circulator also performs the time out prior to incision. The time out is a pause in activity allowing the team to confirm that the correct patient is in the room, the correct site of surgery has been marked, and if there are any known drug allergies. The circulating nurse is responsible for the medical care of the patient until the recovery room staff takes over. It is important that the monitoring team is identified during the time out and that you document the time out in your case log. This is a Joint Commission requirement and many monitoring organizations are now Joint Commission accredited.

The anesthesiologist is a physician responsible for putting the patient to sleep, maintaining the patient in an anesthetized state during the procedure, and waking the patient up after surgery. The anesthesiologist is responsible for the medical care of the anesthetized patient. An anesthesiologist may be responsible for multiple rooms simultaneously and must be assisted by a member of the anesthesia team that is always present with the patient. This may be an anesthesiology resident (an anesthesiologist in training) or a nurse anesthetist. A nurse anesthetist is known as a CRNA, which stands for certified registered nurse anesthetist. The neuromonitoring team must communicate effectively with the anesthesia team. The choice of anesthetic may greatly affect the success of neuromonitoring. It is important to remember that the priority lies with the anesthesiologist keeping the patient anesthetized and medically stable. With that in mind, it is paramount that the neuromonitoring team communicates clearly with the anesthesia team and shows deference to their critical responsibilities. Your responsibility is to inform the anesthesia team of the surgeon's request for monitoring and what anesthetic regimens may be hostile to the success of monitoring. A good anesthesia team will be able to work around your requests accommodating both the monitoring team and other considerations, but you must always defer to anesthesia. Document your conversations with the anesthesia team in an accurate and professional manner. This can be very important later if there is a postsurgical complication.

The surgical technologist or scrub tech is responsible for sterilizing the instruments and setting up the instrument table. During the procedure the scrub tech will hand the surgeon instruments and is responsible for counting supplies both before and after the procedure. This safeguard ensures nothing is left inside the operative site. The scrub tech may be a nurse but may be a graduate of a 2-year training program in surgical technology.

Intraoperative imaging techniques are often used during spine surgery to assist the surgeon with identifying the correct level and determining the adequacy of instrumentation. A radiology technologist is present in the room to operate the imaging equipment. The most commonly encountered imaging equipment in the OR is the C-arm. Since there may be multiple rooms requiring the services of the radiology tech, this person may come and go during the procedure.

If hardware or other implants are to be used during the surgery, there will be a representative (often called a "rep") in the room that is trained in the use of the hardware or implants. This person is a hybrid sales person/technician and is usually not authorized to lay hands on the patient. Instead this person guides the surgeon in the appropriate use of the product and is there to troubleshoot issues that arise with the use of the product.

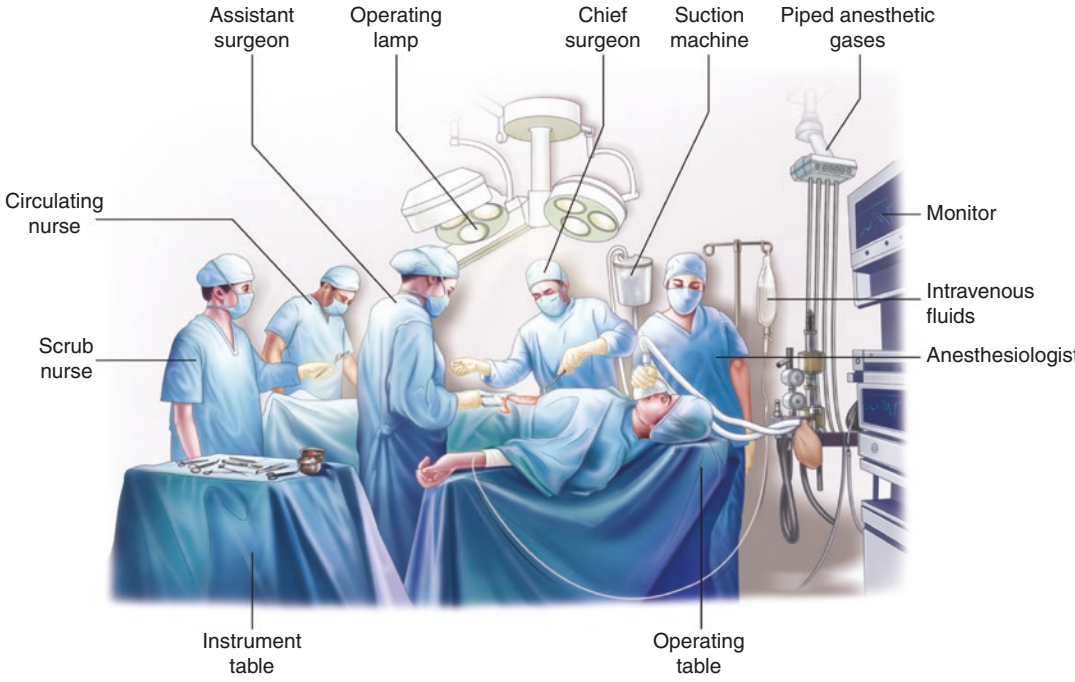

Fig. 1.3 Members of the OR team conducting a surgery

Each member of the team has an important role to play in ensuring a safe and effective surgery. This team approach often results in a mutual respect among the members of the team. It is common to see all team members thanking each other at the conclusion of a surgical procedure (Fig. 1.3).

Commonly Encountered Equipment

The Operating Table

There are several different types of operating tables to meet the requirements for different surgical procedures. Most share some common features. The ability to adjust the height of the bed as well as its position is a critical feature. The OR table is one of the most common sources of 60-Hz noise seen in IOM recordings. The table may be unplugged when its controls are not being used in order to eliminate the source of noise (Fig. 1.4). Always check with the surgeon prior to unplugging the bed.

Electrosurgical Unit

The electrosurgical unit (ESU) is also called the electrocautery equipment. This equipment uses high-frequency current to cut through the skin and cauterize bleeding vessels. There are two common types of ESUs, a monopolar and a bipolar. Use of the ESU introduces a high-frequency artifact into the IOM recording that is difficult to average out. The IOM machine should be paused during cautery (Fig. 1.5). *Hint*: That is a common CNIM question. If the high-frequency signal causes your amplifier to saturate, it is necessary to power the base unit off and on again to recover.

C-Arm

The C-arm is an X-ray unit that can provide individual X-ray pictures or aid navigation using continuous fluoroscopy. The C-arm can rotate around the operating table for both anterior–posterior and lateral images and is used to guide the surgeon in the accurate placement of hardware (Fig. 1.6).

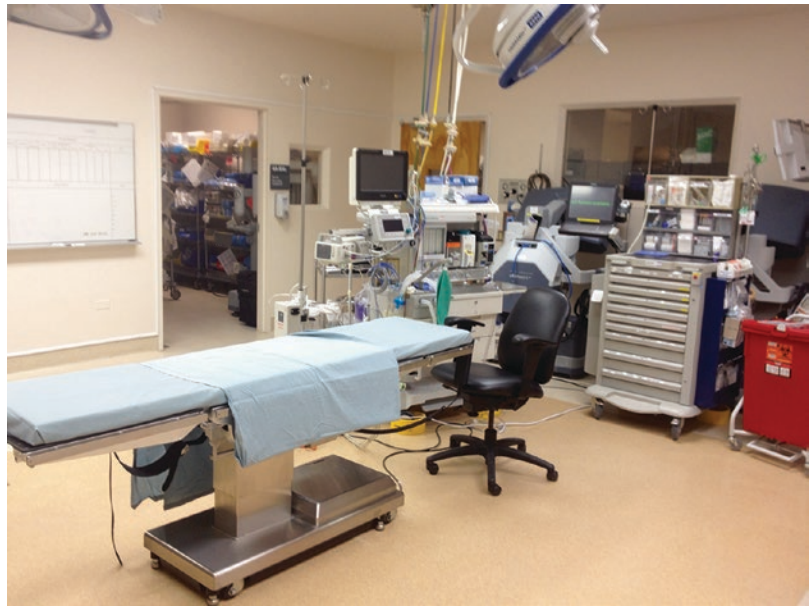

Fig. 1.4 A typical operating table

Fig. 1.5 The electrosurgical units are shown in the *top* and *middle* of the *blue cart*

Fig. 1.6 A C-arm. Notice the clear plastic drape used for sterility when the C-arm is being used. In this photo, the drape has been gathered around the top and is no longer sterile

The Patient Warmer (Bair Hugger)

Patient warmers circulate warm air through a plastic blanket that is draped over the patient during surgery. These machines are often a significant source of electrical noise (60 Hz) introduced into the IOM recording.

The Microscope

The operating microscope is commonly used during intracranial and some spinal procedures. This type of microscope is large and often has two sets of eyepieces allowing two surgeons to operate at once. The controls for the scope are located on the handgrips. There is the option of video output to a monitor allowing others in the operating room to have the same view as the surgeon (Fig. 1.7).

Fig. 1.7 A surgical microscope sterilely draped with a clear plastic drape

Anesthesia Work Area

The anesthesia work area is where you will find both the anesthesia machine and cart. The anesthesia machine is designed to deliver medical gasses and inhaled anesthetics to the patient during surgery. In addition, there are several patient monitoring devices connected to display monitors. You will notice electrical outlets on the back of the anesthesia machine. These are for use by the anesthesia team only. IOM equipment should never be plugged into the back of the anesthesia machine so as to avoid a disruption in power to this critical piece of equipment (Fig. 1.8). The anesthesia cart resembles a large tool chest (and sometimes a tool chest is actually used). The cart contains locking drawers for the storage of injectable medications (Fig. 1.9).

Aseptic and Sterile Environments

It is commonly believed that the operating room is a completely sterile environment. This is not true. The definition of sterility is "free from infective organisms." It would be difficult to maintain the sterility of the entire room with all of the people that must enter and leave before, during, and after a case. Instead, the OR has both sterile and nonsterile components. The nonsterile components, however, are kept aseptic meaning as free of microorganisms as possible. Once an incision has been made, the patient becomes more vulnerable to infection. Therefore, all elements that are going to be in contact with the wound exposure are to be sterile. All other items are nonsterile, but aseptically cleaned.

It is important to be aware of sterile and nonsterile areas of the operating room when moving about. Sterile areas are indicated by the presence of blue drapes that cover tables or Mayo stands where sterile equipment or instruments will be kept during the procedure (Fig. 1.10). Larger items that must remain sterile such as the microscope or C-arm (X-ray)

Fig. 1.8 An IOM station set up behind the anesthesia machine

Fig. 1.9 The anesthesia work station shown at the head of the operating table

will be covered with sterile clear plastic drapes. Sterilizing such large equipment itself is not possible, so covering with a sterile drape achieves the same effect. When walking about the room, it is imperative that you keep a distance of at least 18″ from any sterile areas (another common CNIM question). It is advisable to keep sterile areas in front of you to avoid accidental contact from behind that you may not even be aware of. If any part of your body or clothing comes in contact with a sterile surface, do not panic, but do make the circulating nurse or another member of the surgical team aware of it so that they can redrape the area or re-sterilize the instruments. You will gain the respect of the team with your honesty, whereas an attempt to hide your gaff could be disastrous to both your patient and your career.

Fig. 1.10 A surgical technologist stands in the foreground opening sterile items and placing them on the sterilely draped tables as indicated by the *blue drapes*. In the background, an anesthesiologist gets ready for the patient

Anything that will come in contact with the operative wound must be sterilized. The process of sterilization kills all microorganisms on the surface of the item and prevents the transmission of microorganisms from the item to the patient. Once the item is sterilized, personnel who are in sterile gowns and wearing sterile gloves are the only people that may handle it. Sterilization is achieved on-site by placing the items in an autoclave. The autoclave uses high temperature and pressure to kill all microorganisms on the items. Many disposables that are used in surgery are sterilized at off-site locations where they are manufactured. These items, often plastic, may undergo sterilization using a gas called ethylene oxide (EtO). This method of sterilization is used on any equipment that cannot tolerate the high heat of more traditional methods of sterilization. Sterile items are easily identified by being loosely wrapped in a blue cloth. Another indication that instruments are sterile is if they are laying in a metal tray on top of a table that is draped in blue. Prepackaged disposable items will usually be double packaged in clear plastic with a label indicating that the contents are sterile.

In addition to sterilization of instruments that will come in contact with the operative wound, it is equally important to sterilize the area of skin where the incision is to occur. This is called skin prepping. Prepping a surgical site on a patient involves shaving the skin around the incision, scrubbing the skin with a disinfectant solution such as iodine, and then outlining this newly sterile area by taping a blue sterile drape to the patient's skin. This process creates a sterile window in which the surgeon will work. All personnel that will have contact with the instruments or the operative wound must be "scrubbed in." This means that they must carefully scrub their hands, fingernails, and arms and then don a sterile gown over their scrubs as well as sterile gloves. Personnel that are scrubbed in are to be considered sterile from fingertips to elbows and waist to shoulders (Fig. 1.11). They are not considered sterile from the waist down or from behind. Once someone is scrubbed in, you should avoid contact with these areas of their body, and they will avoid contact with any surface that is nonsterile. The members of the surgical team that go through this process are the surgeon, the surgical technologist (often called the scrub tech), and any other personnel assisting the surgeon with the procedure such as a physician assistant.

Fig. 1.11 An example of personnel "scrubbed in." Notice they are sterile in the front from the waist up and from the fingertips to the elbows

It is the responsibility of all team members to help avoid the spread of infection. Handwashing is the number one defense against infection both in and out of the OR. Hands should be washed before and after contact with each patient, when hands are visibly soiled, and when there has been any contact with surfaces suspected of containing microorganisms. The proper technique for washing hands includes wetting the hands and applying soap and then scrubbing the hands thoroughly up to the forearms for a minimum of 20 s. Hands should then be rinsed in warm water and dried with a clean towel. Handwashing for the processes of "scrubbing in" is a more methodical process that involves a long-acting antimicrobial soap, scrubbing each fingernail in detail, and always scrubbing up to the elbows. This procedure takes a minimum of 5 min.

Communication and Documentation

A team is only as good as the weakest member. Each member of the team should understand their role and seek to carry that role out to the best of their ability, leaving behind any distractions or personal issues. The goal of each team member is to ensure a safe and effective surgical procedure. Achieving this goal requires proper communication and documentation. In order for the surgeon to concentrate on the procedure at hand, he or she must trust that the patient is being properly cared for and monitored by other members of the care team.

The neuromonitoring clinician must work with both the anesthesiologist and the surgeon to successfully accomplish the mission of monitoring the patient's nervous system during surgery. Information relayed from the neuromonitoring team to the surgeon or anesthesiologist can change the course of the surgery and avoid a negative neurological outcome for the patient. Inaccurate information regarding neuromonitoring data can harm the patient either by failing to detect an emerging injury or by creating a necessary pause or stop to surgery based on a false alarm. To ensure a successful outcome, three-way communication between the surgeon, anesthesiologist, and neuromonitoring clinician is essential.

It is essential that the communication between the surgeon, anesthesiologist, and neuromonitoring clinician be well documented. The IOM clinician should have conversations with the surgeon and anesthesiologist regarding the monitoring plan prior to the patient coming back to the OR. As the neurophysiological monitoring expert, you should present an appropriate monitoring plan to the surgeon for approval. The surgeon will have the opportunity to ask questions about a particular modality or to request that changes are made to the monitoring plan. It is much more difficult to have this conversation in the OR during the busy process of preparing for surgery. This conversation should be documented in the monitoring record, especially if the surgeon's requests are outside of commonly accepted monitoring protocols.

Communication with the anesthesiologist prior to surgery is also essential. You should discuss the monitoring plan with the anesthesiologist including the effects of particular anesthetic regimens on the ability to collect monitoring data. At this time, contraindications to motor evoked potentials should be discussed as well as the location of all needle electrodes. If running motor evoked potentials, ask that the anesthesiologist place a soft bite block bilaterally. Document these communications thoroughly in the monitoring record.

Review Questions

1. What should you do if you suspect that a piece of equipment in the OR is causing significant electrical artifact in your monitoring signal?
2. You have a sterile electrode that will be required for stimulating later in the procedure. Who should you give this to?
3. What should you do if the anesthesia team is uncooperative with the monitoring plan and insists on a regimen that will prevent you from successfully recording data that the surgeon requests?

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2 Anatomy of Intraoperative Monitoring

Scott Francis Davis

Introduction

Structure and function are intimately related. There is an old adage that structure subserves function. This is at once a simple and yet profound statement. Look around your environment and you will prove this concept to yourself time and again. A coffee cup, by necessity, has a hole at the top and not at the bottom. Its structure subserves the function of holding coffee. The human body is no less practically created. As an IOM professional you are tasked with protecting neural structures and functions at risk during surgery. An intraoperative neurophysiologic monitoring curriculum, therefore, must include a foundation in anatomy.

The neuromonitoring professional does not require a detailed knowledge of all anatomical systems but instead benefits from a more focused approach to relevant organs and systems that are directly involved in the monitoring plan. Generally, knowledge of the nervous, skeletal, and muscular systems is the cornerstone of the monitorist's anatomy curriculum. Equally important is the ability of the monitorist to communicate with other members of the care team using accurate anatomical terminology. This chapter provides an easily readable general overview of anatomical terminology and structures important to the neuromonitoring clinician with no previous background in anatomy.

Directional Terminology

The location of anatomic structures can be described using directional terms recognizable by all healthcare professionals. The use of proper directional terminology is necessary to avoid ambiguity with regard to anatomic locations and patient positioning. The most important thing to remember is that the position of anatomical structures can only be described relative to another structure or landmark. For example, the question "Is the thumb medial or lateral?" must prompt the follow-up question "medial or lateral to what?" A correct question would be "Is the thumb medial or lateral to the pinkie?" When answering questions such as this, it is always necessary to place the patient in proper *anatomic position*. The anatomic position is defined as the patient standing erect with the feet facing forward and slightly apart (Fig. 2.1). The hands are down at the sides with the palms facing forward. If we go back to our sample question, we say that the thumb is lateral (further from midline) to the pinkie. If we rotate the patient's hand such that the palms are now facing behind, the answer to our question did not change! This is because we must always reorient the patient to the anatomic position in our mind.

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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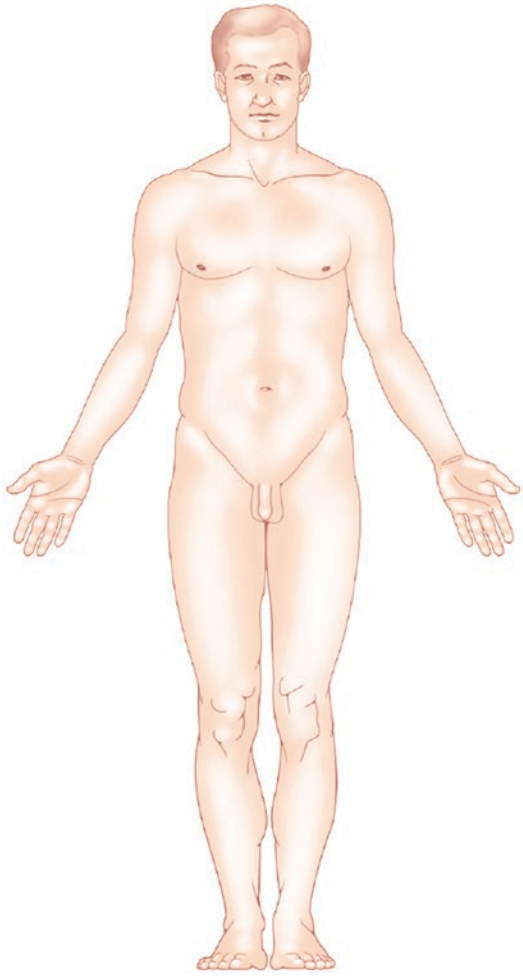


Fig. 2.1 The human body in anatomic position

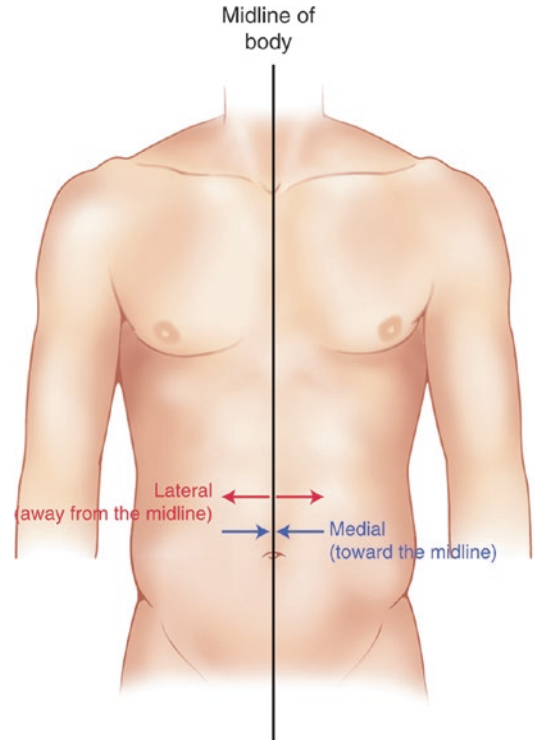


Fig. 2.2 Drawing of a human torso with the anatomic midline shown in *black*. *Arrows* indicate the relative terms of medial and lateral

The human body has a line of symmetry that bisects the body into right and left equal halves. This line of symmetry is known as the *midline*. Structures relatively further from midline than a reference structure are *lateral*, while structures lying closer to midline are said to be *medial* to the reference structure (Fig. 2.2).

The terms *proximal* and *distal* refer to locations that are closer to or further away from the point of attachment of a limb. These terms are often used to describe the position of structures along a limb relative to each other. For example, the elbow is distal to the shoulder but proximal to the wrist.

Superior and *inferior* are terms that refer to the position of a structure either above or below a reference point, respectively. For example, one can expect to find the nose superior to the chin in most people.

Humans, being bipedal, require some additional terminology than our quadruped friends. In other organisms, the terms anterior and posterior have different meanings than dorsal and ventral. In humans, we often speak of the *anterior* and *posterior* portions of a limb or the torso. The anterior side is "belly side," and the posterior is "back side." These terms are synonymous with *ventral* and *dorsal*, respectively (Fig. 2.3). We begin to confuse these terms when considering directionality along the neuraxis.

The curvature of the neuraxis necessitates the introduction of two additional directional terms: *rostral* and *caudal*. The term rostral (from the Latin for nose) refers to points located further toward the nose on the neuraxis than the referenced structure. Caudal (from the Latin for tail) refers to points located further toward the

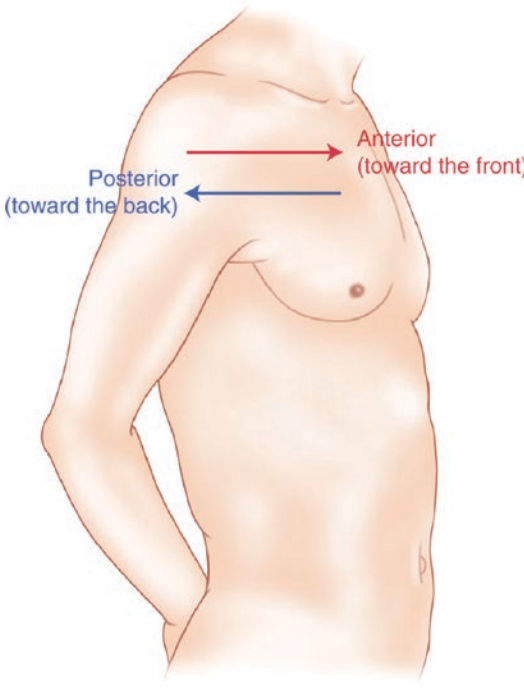


Fig. 2.3 A lateral drawing of the human trunk with *arrows* indicating the relative terms of anterior and posterior

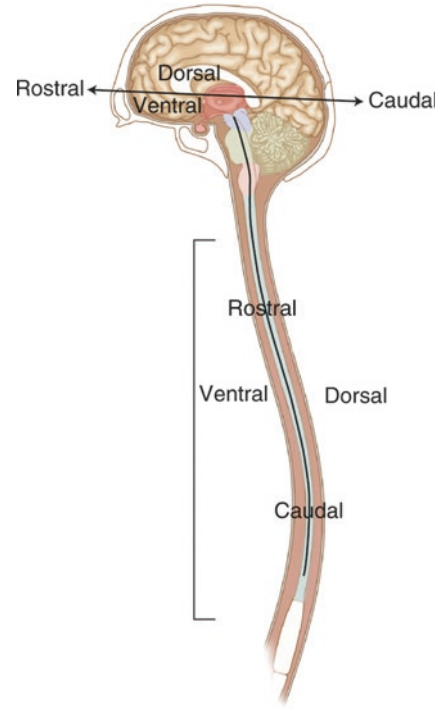


Fig. 2.4 A drawing of the neuraxis illustrating the relative terms rostral, caudal, dorsal, and ventral

end of the spinal cord. The rostral–caudal axis will bend with the neuraxis (most notably as you approach the level of the cerebral cortex). The dorsal–ventral or anterior–posterior plane is perpendicular to the rostral–caudal axis at any given point (Fig. 2.4).

Pathways moving from the peripheral nervous system toward the central nervous system are termed afferent pathways. These pathways are sensory. Pathways that travel from the central nervous system out toward the periphery are termed efferent pathways. These pathways carry motor information.

Organization of the Nervous System

The nervous system can be divided both anatomically and functionally. Anatomically we divide the nervous system into the central and peripheral nervous system. The central nervous system (CNS) consists of the brain, spinal cord, and retina. The peripheral nervous system (PNS) consists of all of the nerves that come off of the brain (cranial nerves) and spinal cord (spinal nerves), nerve plexuses, and peripheral nerves innervating the various structures of the body.

Functional divisions of the nervous system include the somatic and autonomic divisions. The somatic nervous system governs voluntary actions and provides motor output through the action of the skeletal muscles. We will spend the majority of time discussing the somatic nervous system, as it is the division that is amenable to neuromonitoring. However, a brief consideration of the autonomic nervous system is warranted.

Autonomic Nervous System

The autonomic nervous system governs "automatic" visceral or vegetative functions and operates generally at the unconscious level. Examples

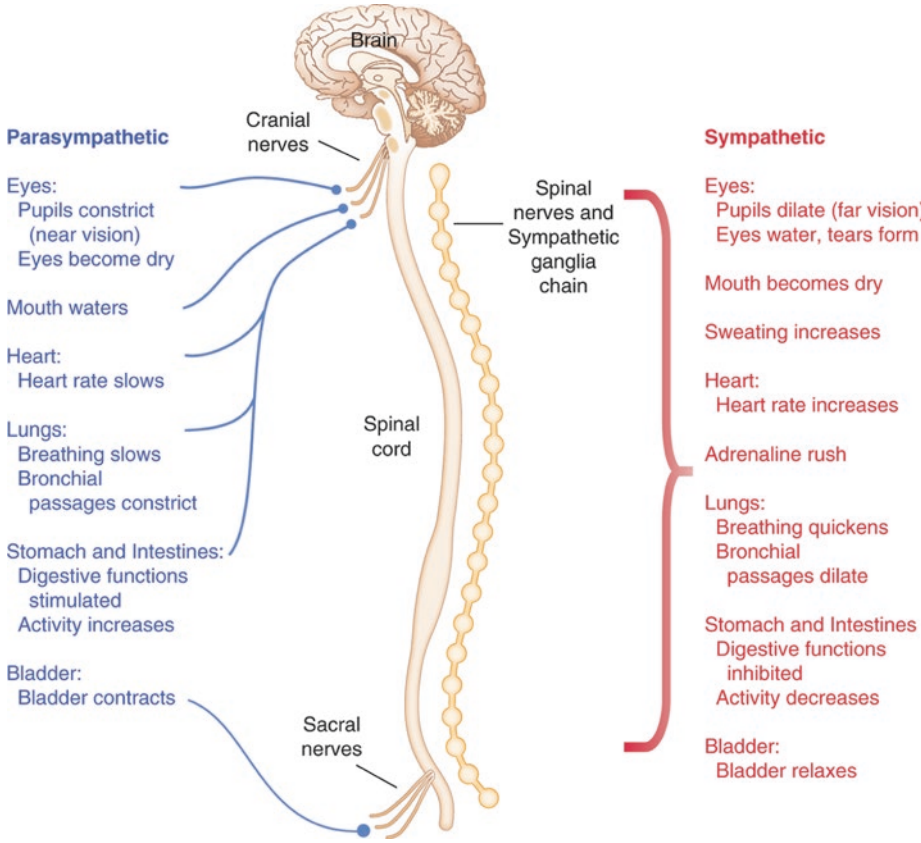


Fig. 2.5 The organization and function of the autonomic nervous system are shown. The parasympathetics are shown in *blue* on the *left* originating from cranial nerve nuclei and sacral spinal nerves. On the *right*, shown in *red*, are the sympathetics originating from thoracolumbar spinal nerves

of functions under autonomic control include respiration, heart rate, digestion, and sexual arousal. The autonomic nervous system has two divisions: sympathetic and parasympathetic (Fig. 2.5).

The sympathetic nervous system has its anatomic origin from the thoracolumbar segments of the spinal cord, which is why it is sometimes called the thoracolumbar division of the autonomic nervous system. The sympathetics are responsible for the well-known "fight-or-flight" response. Consider what would happen if you were to encounter a bear in the woods (or any foreboding situation that you can imagine). Your body would prepare to either fight the bear or run from it. To do this you would need increased oxygen delivery to your muscles. The result is an increase in respiration and heart rate. Your pupils would dilate in order to increase visual acuity, and your hair would stand on end so that you may appear more ferocious to the bear (this last part may be an evolutionary leftover).

The parasympathetic division is anatomically located on either side of the sympathetic division and is alternately called the cranial–sacral division. The prefix "para" meaning "alongside" will remind you of the location. The parasympathetic division of the autonomic nervous system regulates visceral functions at rest. The phrase "rest and digest" summarizes the function of the parasympathetic system. You will study the cranial nerves in another section, but if a cranial nerve has an autonomic function, you can be sure it is parasympathetic. Again, remember that the parasympathetics have cranial or sacral origins. The vagus nerve (CNX), for example, is the largest parasympathetic nerve in the body.

Somatic Nervous System

The somatic nervous system governs voluntary movement as well as sensory processing of sensory information from external stimuli (such as light, sound, and touch). The somatic nervous system is that division that is tested during intraoperative monitoring. The somatic nervous system works through the activation of skeletal muscles and exteroceptors.

When discussing the somatic nervous system, it is common to specify between sensory and motor pathways. Sensory pathways are those that are activated by sensory stimuli in the environment and transmit this information to the central nervous system. There are many different sensory stimuli in our environment from light and sound to pain and temperature and many modalities in between. In order to be interpreted by the nervous system, these sensory modalities must be changed into electrical impulses. The process by which sensory stimuli are converted to electrical impulses for use by the nervous system is called *transduction*.

All sensory neurons have specialized endings called *exteroceptors* that are specific for the sensory modality they mediate. For example, exteroceptors in the retina are called photoreceptors. Hair cells are the sensory cells of the auditory system. Sensory neurons that mediate various types of mechanical stimuli in the skin have different names like Pacinian corpuscles for deep touch and pressure or Meissner's corpuscles for light touch (Fig. 2.6). Proprioception, knowing where your limbs are in space, is mediated by stretch receptors located in the muscles.

We are able to stimulate and record from both sensory and motor pathways in order to assess their function either in the clinic or during surgery. We will continue our discussion of neuroanatomy with a focus on sensory and motor tracks of the somatic nervous system. In subsequent

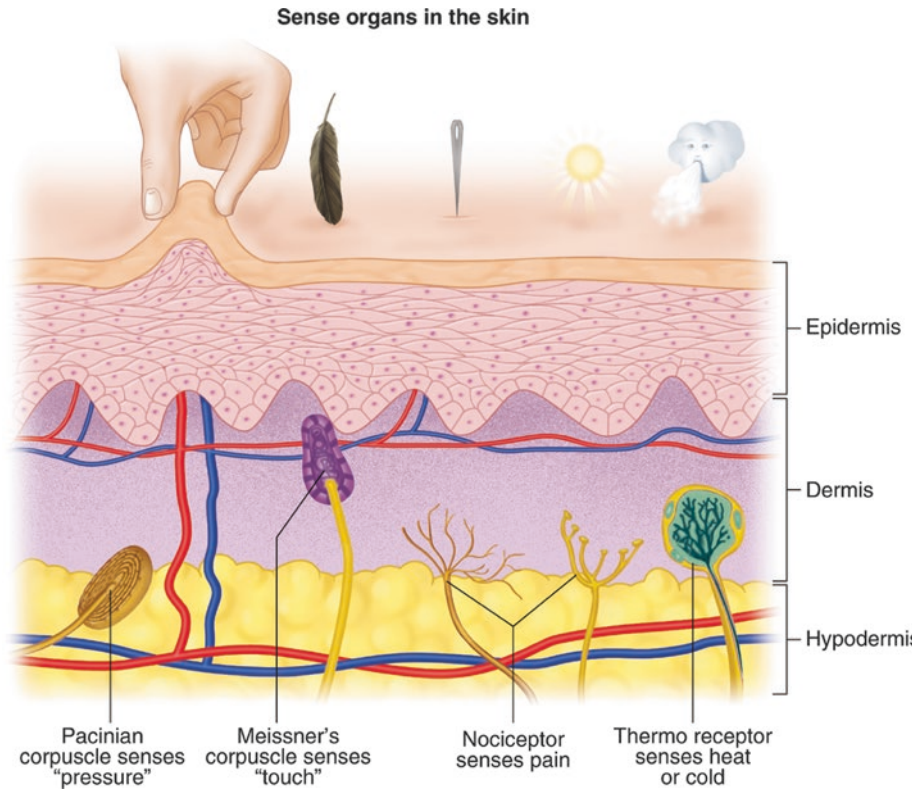


Fig. 2.6 Various sensory organs of the skin along with their function

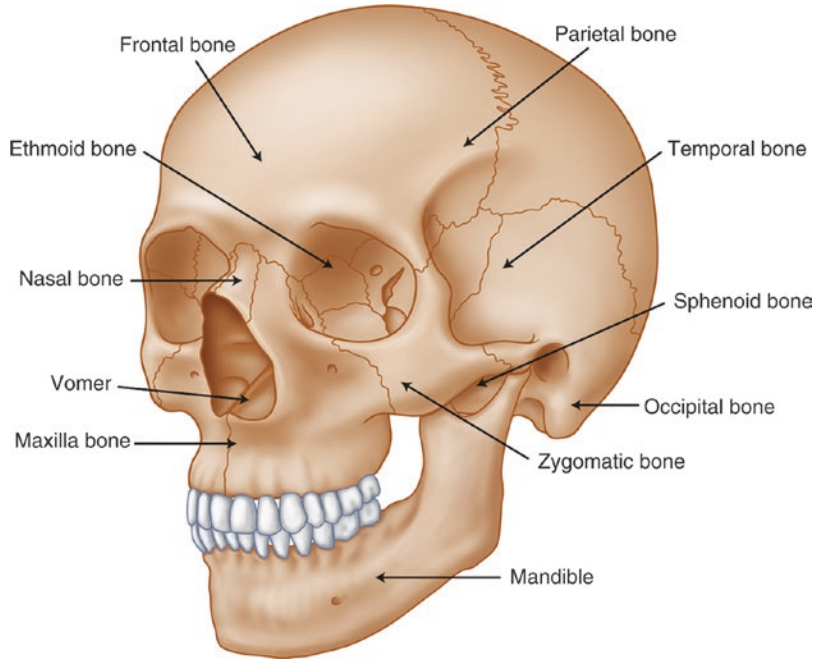


Fig. 2.7 The cranial bones including the frontal, parietal, temporal, and occipital bones along with the mandible comprise the complete human skull

chapters, you will learn how we can stimulate and record from these anatomical substrates for the purposes of intraoperative monitoring.

Brain Anatomy

The human brain is arguably the most complex structure in existence. The brain governs all of human behavior. Vegetative functions are controlled by the lower brain structures of the brainstem, while reasoning and other distinctly human behaviors are a result of processing in higher brain centers such as the cerebral cortex. An understanding of the overall structural organization of the brain with a focus on sensorimotor processing is required for the IOM clinician to properly plan, carry out, and interpret a monitoring session. In this section, we will discuss the gross anatomical organization of the brain including topographical organization. We will consider some important neural pathways in a subsequent section.

The Skull

The brain is protected by a bony structure called the *cranium*. The cranium, along with the mandible, makes up the *skull* (Fig. 2.7). The uppermost part of the skull is known as the skull cap or *calvarium*. The skull serves as a protective case for the brain. Bones of the skull are joined together by special immobile joints known as *sutures*. In infants, the skull bones are separated by cartilaginous areas known as *fontanelles* (Fig. 2.8). The fontanelles allow for expansion of the skull to accommodate the growth of the brain. The fontanelles are mostly ossified by 2 years of age.

The Meninges

The brain and spinal cord are further protected by a system of membranes called *meninges*. The meninges consist of three layers that are anatomically continuous: the *dura mater*, the *arachnoid mater*, and the *pia mater*. The term dura mater is from the Latin word literally meaning "tough mother," while pia mater means "soft mother." The word arachnoid implies a spider-web-like quality. The function of the meninges is to protect the brain and contain cerebrospinal fluid (Fig. 2.9).

The dura mater is the fibrous outermost layer of the meningeal membranes. This layer contains

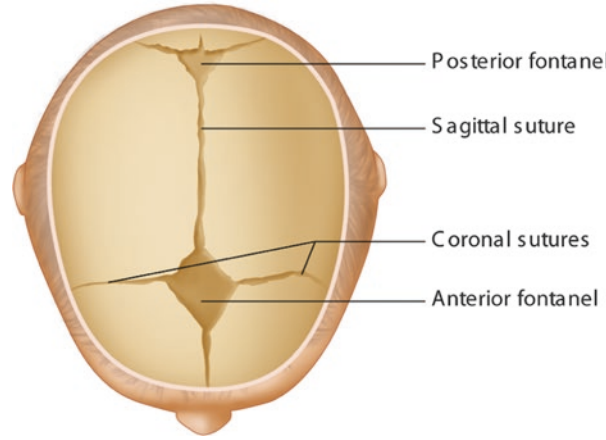


Fig. 2.8 Superior view of the infant skull showing the anterior and posterior fontanelles along with the development of the sagittal and coronal sutures

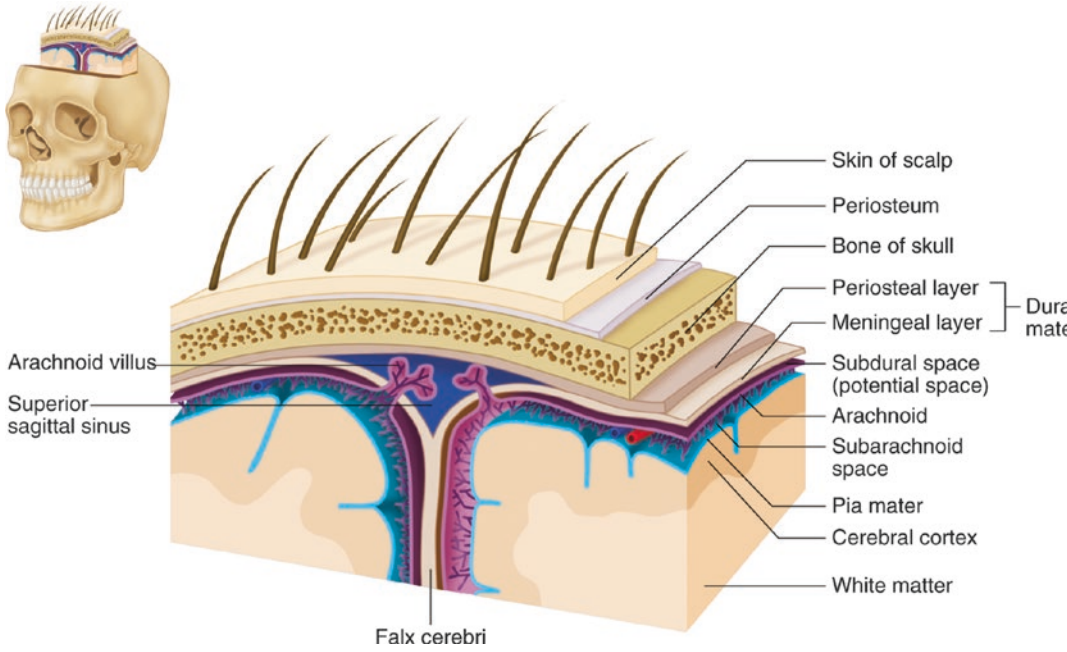


Fig. 2.9 The organization of the meninges and meningeal spaces of the brain

larger blood vessels as well as sensory nerve fibers. Among the blood vessels present in the dura mater are large venous sinuses that return blood and cerebrospinal fluid from the brain back to the heart. There are two dural extensions that you should be familiar with. The *falx cerebri* separates the cerebral hemispheres and the *tentorium cerebelli* separates the occipital lobe from the cerebellum (Fig. 2.10).

The arachnoid mater is thinner than the dura and resembles a loose-fitting sac for the brain. Thin filaments known as *arachnoid trabeculae* extend from the arachnoid to the pia mater.

The pia mater is the thinnest layer of the meninges and closely adheres to the surface of the brain and spinal cord following each gyrus and sulcus. The pia has an extensive capillary network that nourishes the surface of the brain and spinal cord.

There is a normally occurring space between the arachnoid and pia mater. This *subarachnoid space* is filled with cerebrospinal fluid. Bleeding

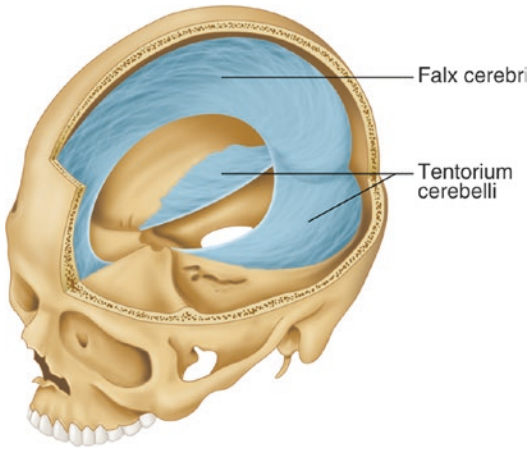


Fig. 2.10 The specialized dural infoldings: falx cerebri and tentorium cerebelli

into this space as a result of trauma or the spontaneous rupture of a blood vessel can enlarge this space causing compression on the brain. This is known as a *subarachnoid hemorrhage* and requires surgical intervention to decompress the neural tissue. The dura and arachnoid are normally attached closely. Occasionally bleeding resulting from trauma or disease will occur opening up a space between the dura and arachnoid that does not normally exist. This potential space is called the *subdural space*, and the resulting bleed or clot would be known as a *subdural hemorrhage* or *subdural hematoma*, respectively.

The Ventricles

There are a series of canals within the brain whose function is to circulate cerebrospinal fluid. These are known as the *cerebral ventricles* (Fig. 2.11). There are two paired (left and right) lateral ventricles, a third ventricle, and a fourth ventricle. The ventricles communicate with each other via foraminal openings and are continuous with the central canal of the spinal cord. The left and right ventricles communicate with the third ventricle through the intraventricular foramina (of Monro). The third ventricle communicates with the fourth through the cerebral aqueduct (also known as the aqueduct of Sylvius). Cerebrospinal fluid returns to the subarachnoid space and venous circulation from the fourth ventricle via the midline foramen of Magendie and two paired foramina of Luschka.

The *cerebrospinal fluid* (CSF) bathes and cushions the brain and spinal cord and is contained within the dura mater. The CSF is produced by tufts of tiny capillaries called *choroid plexus* that are found within the ventricles (Fig. 2.12). CSF is simply filtrated blood plasma. CSF comes from the blood and must eventually return to the blood. The presence of microorganisms or white blood cells in CSF indicates infection within the central nervous system. CSF can be sampled for diagnostic purposes by lumbar puncture.

The Cerebral Lobes

The cerebral cortex can be divided into four paired functional lobes: frontal, parietal, temporal, and occipital (Fig. 2.13). The cortex is the substrate for all higher-order sensorimotor processing and cognitive functioning. If you recall the adage "structure subserves function," it will not be a surprise that the wrinkled structure of the cerebral cortex serves to increase surface area without necessitating an obnoxiously large skull to house the brain! Think of this as folding a piece of paper up to fit into your pocket. The bumps along the brain are called gyri (the singular form is gyrus), and the grooves separating the gyri are known as sulci (the singular form is sulcus). Each gyrus and sulcus of the brain has its own name. We will just consider a few.

The frontal lobe is responsible for higher-order executive functioning such as personality, inhibition, and long-term memory. From the perspective of the intraoperative monitoring clinician, the frontal lobe is important because it governs voluntary motor function. Premotor and supplementary motor areas of the frontal lobe are not completely understood but are generally accepted to participate in the planning of movement and coordination of sensory and motor information. Direct voluntary motor control, however, begins on one particular gyrus of the frontal lobe known as the *precentral gyrus*. The precentral gyrus gets

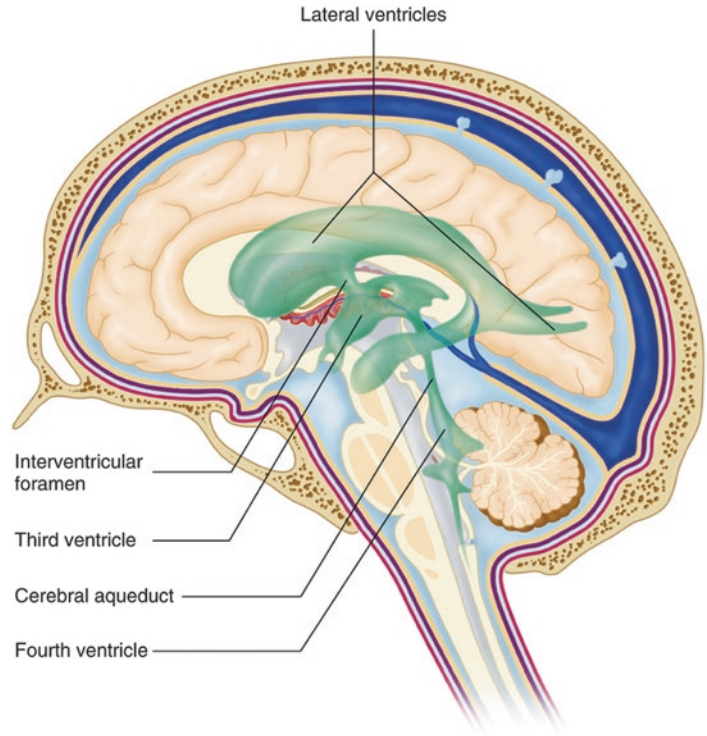


Fig. 2.11 The organization of the cerebral ventricles

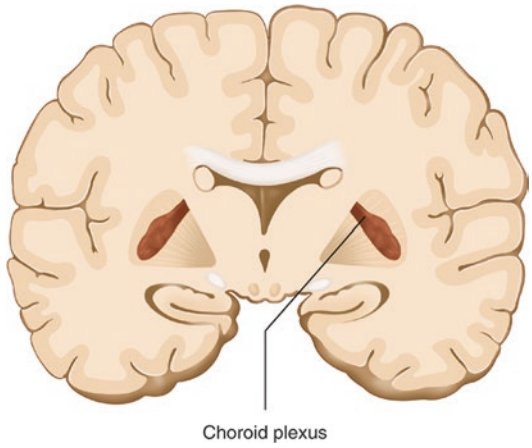


Fig. 2.12 The choroid plexus lines the ventricles making CSF

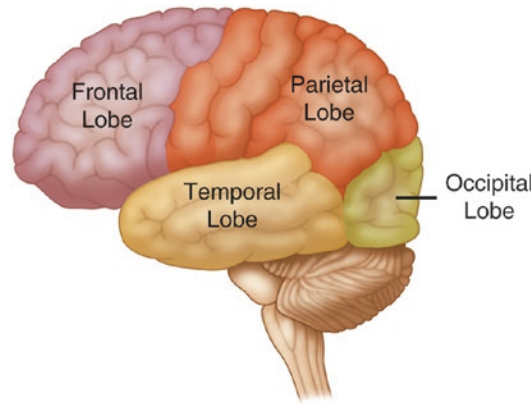


Fig. 2.13 The anatomic lobes of the cerebral cortex

its name from its location anterior to the *central sulcus*. The central sulcus separates the frontal from the parietal lobes of the cerebral cortex. The precentral gyrus is also known as the *primary motor cortex*. Neurons of the precentral gyrus project directly to the spinal cord to influence voluntary movement.

Logic tells us that if there is a precentral gyrus then there must be a *postcentral gyrus*. This gyrus is located in the parietal lobe just posterior to the central sulcus and is also known as the *primary sensory cortex*. Neurons in the postcentral gyrus receive input from the somatic sensory pathways (Fig. 2.14).

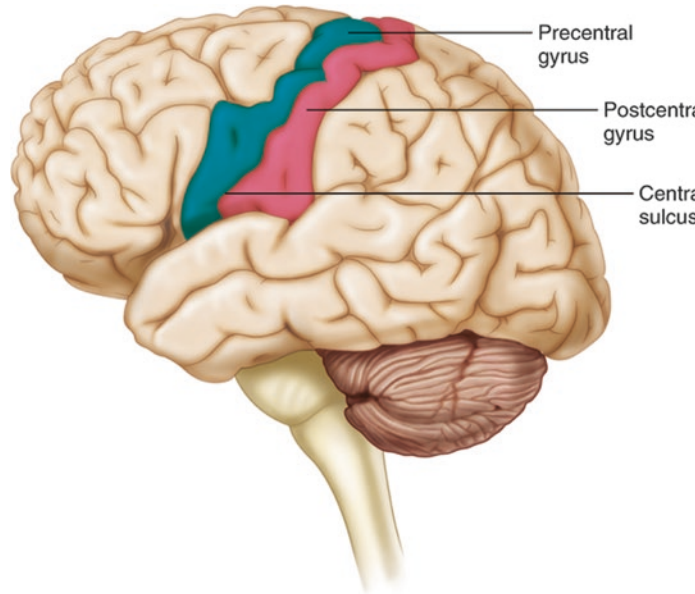


Fig. 2.14 The central sulcus shown with the precentral gyrus (primary motor cortex) and postcentral gyrus (primary sensory cortex)

The lateral sulcus (also known as the Sylvian fissure) separates the frontal and parietal lobes from the temporal lobe. The temporal lobes are responsible for the formation of short-term memories as well as speech and language comprehension.

The occipital lobes are the most posterior lobes of the cerebral cortex. The occipital lobes are the site of visual processing. The calcarine sulcus separates the parietal and occipital lobes. This sulcus runs deep and is not completely visible from the cortical surface.

Topographical Organization

A common theme running through the nervous system is topographical organization. One of the main examples of topographical organization within the brain is the homunculus. The primary motor and primary sensory cortex are functionally organized such that a visual representation of the body may be reconstructed on them (Fig. 2.15). There are slight differences between the motor homunculus and sensory homunculus, but overall, they are quite similar. You will notice that the hands and feet of the homunculus are quite large. This is because there is a proportionately large amount of surface area dedicated to these structures on the cerebral cortex. The hand and face areas are represented laterally, while the lower extremities and genitalia are represented medially. Correlating homuncular topography with cerebral blood supply and recorded electrical potentials will be important for intraoperative monitoring. You will soon learn that the middle cerebral artery supplies the lateral portions of the cerebral hemispheres and the anterior cerebral artery supplies the medial portion of the hemispheres. Deficits resulting from an MCA territory infarct will present clinically in the upper extremity and face. Deficits resulting from an ACA infarct will present clinically in the lower extremity. The homunculus has practical use when determining sites to stimulate and record from the brain for intraoperative monitoring.

The Diencephalon

The diencephalon is a region of the neuraxis, rostral to the midbrain, composed of a group of deep brain structures including the thalamus and hypothalamus (Fig. 2.16). The hypothalamus is often called the master endocrine gland of the body. The thalamus is a bilateral structure composed of

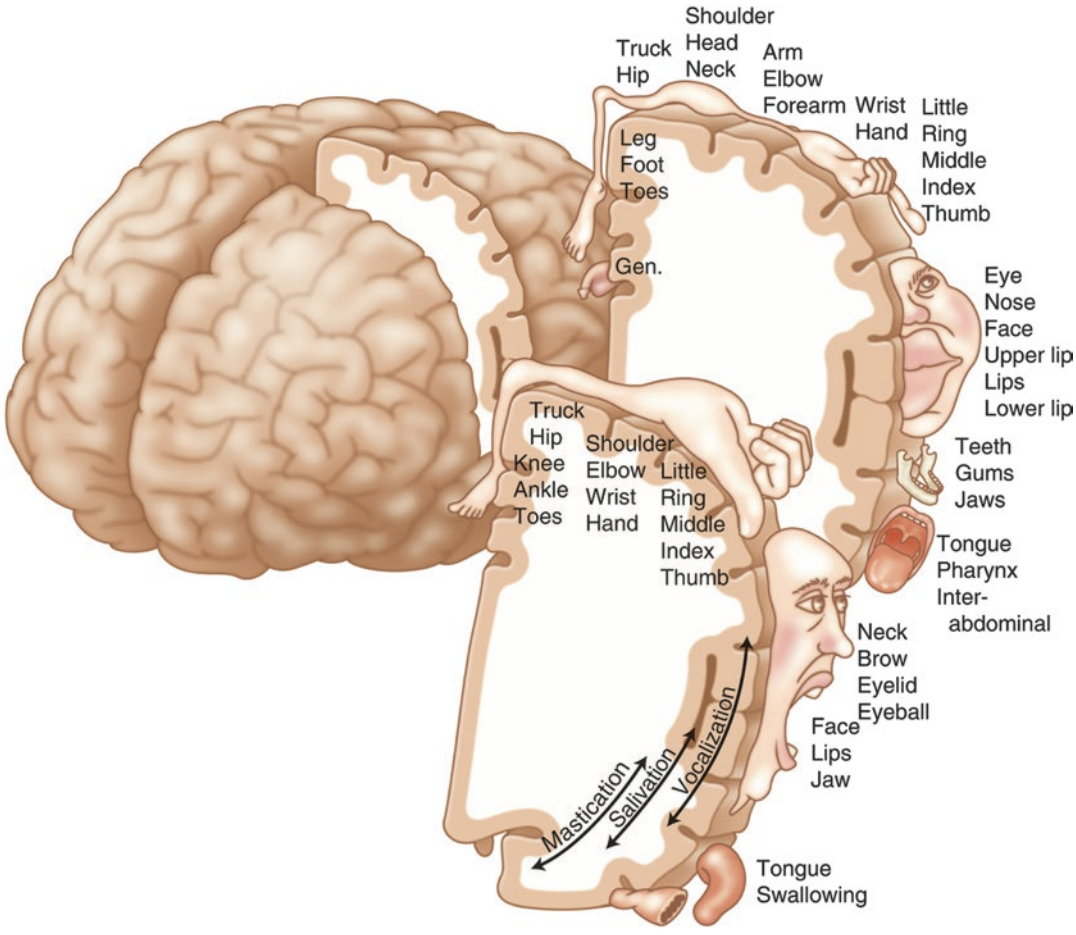


Fig. 2.15 Drawing of the motor and sensory homunculus. Notice that the face and upper extremity are represented laterally and the lower extremity and genitalia are represented medially

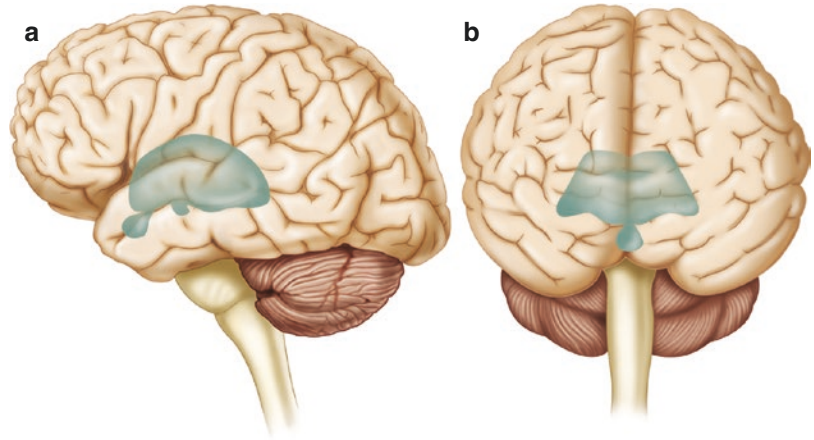


Fig. 2.16 Lateral (**a**) and anteroposterior (**b**) views of the diencephalon (*shaded*) within the neuraxis

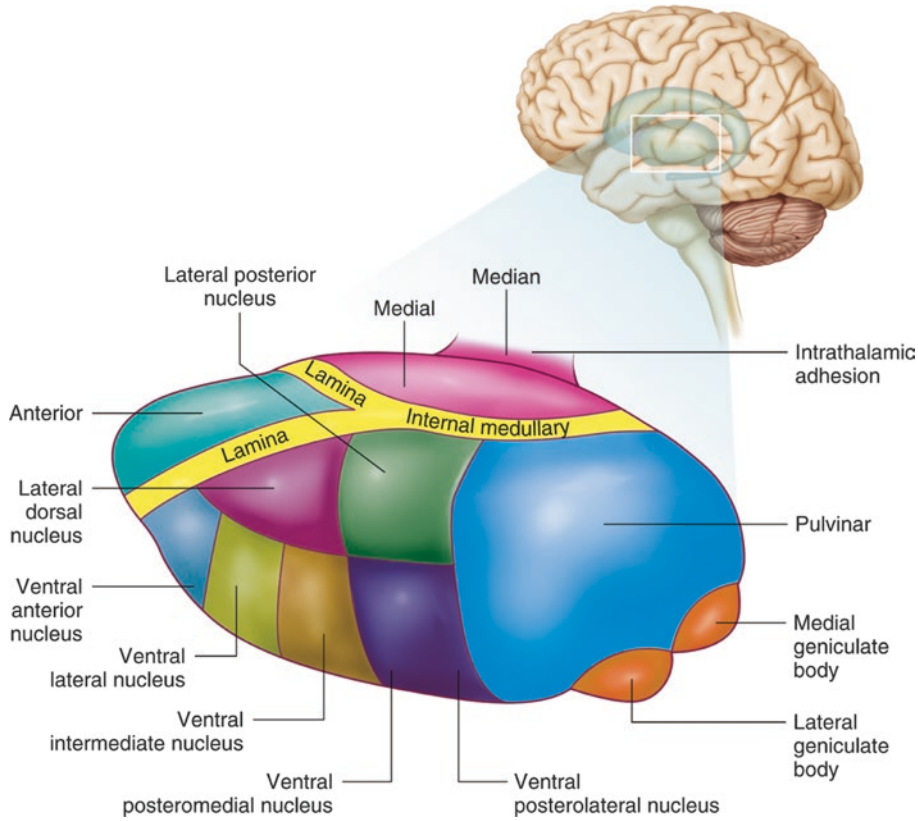


Fig. 2.17 Organization of the human thalamus

several functionally distinct nuclei (Fig. 2.17). Sensory information on its way to the cortex is first processed in the thalamus. The thalamus generates potentials that can be recorded from the scalp during intraoperative monitoring. Blood supply to the thalamus is from the posterior cerebral circulation making thalamic generated evoked potentials useful for monitoring posterior ischemia.

The Brainstem

The brainstem is composed of the midbrain, pons, and medulla oblongata and is continuous with the spinal cord (Fig. 2.18). The brainstem contains sensory and motor tracts passing information to and from the higher brain centers as well as cranial nerve nuclei. The cranial nerve nuclei contain the cell bodies whose axons form the cranial nerves, which supply sensory and motor innervation to the head, neck, and face. Vegetative functions are controlled by the brainstem including the heart rate, respiration, and aspects of the sleep–wake cycle. Intraoperative

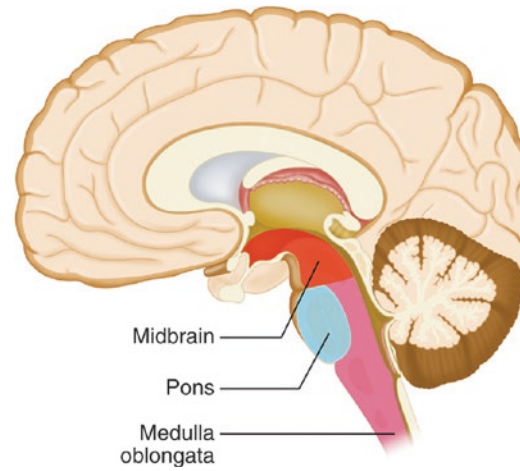


Fig. 2.18 Lateral view of the brainstem (midbrain, pons, and medulla oblongata) within the neuraxis

monitoring of various brainstem potentials can protect these vital structures and functions during surgery. We will discuss some of the brainstem structures in more detail in subsequent sections.

The Cranial Nerves

The cranial nerves emerge from the brain and innervate structures of the head and neck (Fig. 2.19). There are 12 cranial nerves that are motor, sensory, or mixed nerves. Some of the cranial nerves even have autonomic function, specifically parasympathetic function. Each nerve has a unique name but may also be designated by its number. The numerical designation takes the form of "CN" followed by the Roman numeral assigned to the nerve. For example, the facial nerve is also designated CNVII. You should be familiar with both the names and numerical designations of all 12 cranial nerves.

Table 2.1 lists all of the cranial nerves as well as information about each nerve that you should know. There is only one cranial nerve that cannot be monitored and that is CNI, the olfactory nerve, which mediates the sense of smell.

Two of the sensory cranial nerves can be monitored by special evoked potentials. The optic nerve (CNII) and the visual pathway are monitored with visual evoked potentials (VEPs). VEPs are most often carried out in the clinic and are primarily used to diagnose optic neuritis and multiple sclerosis. Intraoperatively, VEPs are used to protect the optic nerve when there is a risk of damaging the nerve during a craniotomy, such as for removal of a tumor near the optic nerve or optic chiasm. Because VEPs are highly sensitive to anesthesia, reliable recordings are often difficult to obtain during surgery.

The vestibulocochlear nerve (CNVIII) is the other cranial nerve that is monitored with the use of special evoked potentials. CNVIII is actually two nerves in one (Fig. 2.20). The vestibular branch innervates the semicircular canals and is important for balance, while the auditory branch innervates the cochlea and mediates hearing. The auditory branch is monitored with the use of brainstem auditory evoked

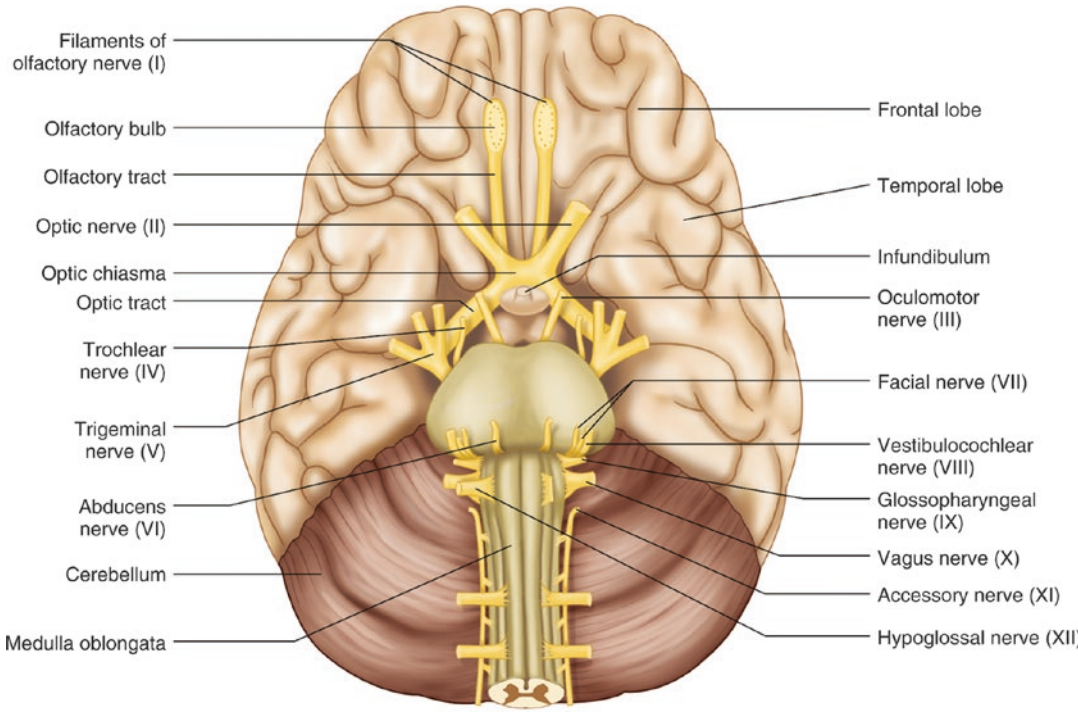


Fig. 2.19 Ventral view of the brain showing the 12 cranial nerves

Table 2.1 The cranial nerves

Number	Name	Modality	Function	Monitored through
I	Olfactory	Sensory	Smell	N/A
II	Optic	Sensory	Vision	VEP
III	Oculomotor	Motor	Eye movement, pupillary constriction	EMG from extraocular muscles (except trochlea and lateral rectus)
IV	Trochlear	Motor	Eye movement	EMG from superior oblique
V	Trigeminal	Both	Sensation to face, motor to muscles of mastication	EMG from masseter or temporalis
VI	Abducens	Motor	Eye movement	EMG from lateral rectus
VII	Facial	Both	Motor to muscles of facial expression, autonomic input to salivary glands, taste to anterior 2/3 of the tongue	EMG from muscles of facial expression
VIII	Vestibulocochlear	Sensory	Hearing and balance	BAEP
IX	Glossopharyngeal	Both	Sensation to tonsils and pharynx, motor to stylopharyngeus, taste to posterior 2/3 of the tongue, input to the parotid gland	EMG from the soft palate
X	Vagus	Both	Parasympathetic to thoracic and abdominal viscera, motor to vocal muscles	EMG from vocal cords (monitors recurrent laryngeal nerve)
XI	Spinal accessory	Motor	Motor to trapezius and sternocleidomastoid	EMG from trapezius
XII	Hypoglossal	Motor	Motor to tongue	EMG from tongue

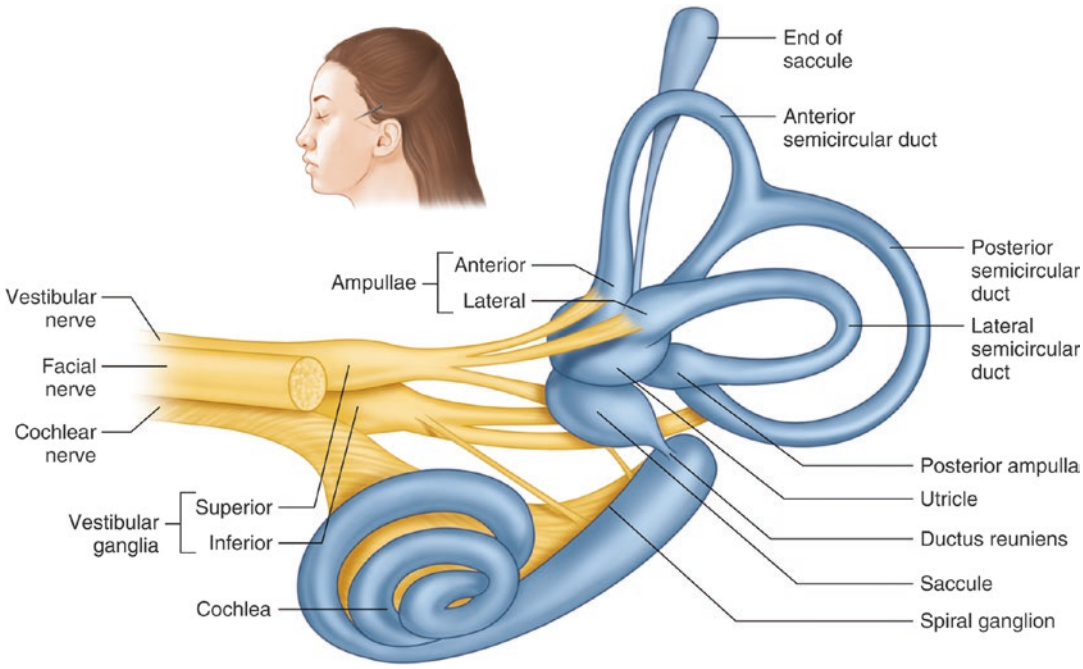


Fig. 2.20 The auditory and vestibular nerves emerge from the cochlea and semicircular canals, respectively, to form CNVIII. Note the association of the facial nerve as it travels with CNVIII through the temporal bone

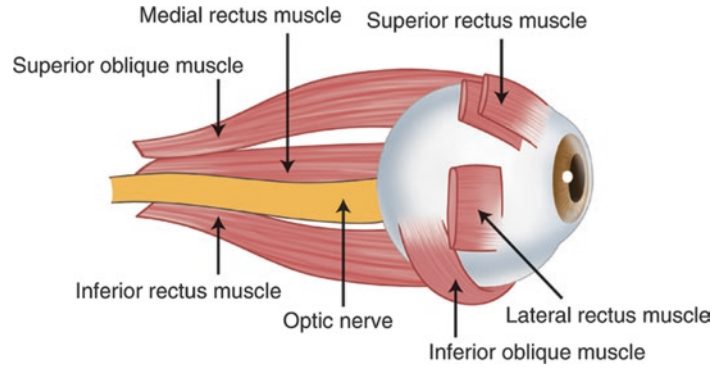


Fig. 2.21 The extraocular muscles

potentials (BAEPs). BAEPs are discussed in another chapter of this book.

Three cranial nerves innervate the extraocular muscles (Fig. 2.21). The oculomotor nerve (CNIII) controls most of the movements of the eye and also governs the pupillary reflex and accommodation. CNIII innervates all of the extraocular muscles except two. The ones innervated by CNIII are the superior rectus, medial rectus, and inferior rectus. A lesion of CNIII produces oculomotor palsy characterized by a lateral and downward deviation in the gaze known as *down and out* symptoms. There are two remaining extraocular eye muscles that are innervated by other cranial nerves.

The trochlear nerve (CNIV) is a somatic motor nerve innervating the superior oblique muscle. The abducens nerve (CNVI) innervates the last remaining extraocular muscle, the lateral rectus. The easiest way to remember the innervation of CNVI is to look at its name, *abducens*. This word means to *abduct*, which is the term for movement away from the midline. Movement away from midline is *lateral* movement. Therefore, the *abducens* nerve innervates the *lateral* rectus muscle.

The cranial nerves III, IV, and VI can be monitored with EMG from the appropriate extraocular muscles. It should be noted, however, that this requires special electrodes that are inserted with small needles and requires specialized training. For these reasons these nerves often go unmonitored.

Spontaneous and triggered EMG is used to monitor all the remaining cranial nerves. When possible, it is advisable to electrically stimulate the nerve directly to confirm identification and function.

The trigeminal nerve (CNV) mediates sensation to the face as well as providing motor innervation to the muscles of mastication, namely, the temporalis and masseter. The trigeminal nerve has three branches: the ophthalmic nerve (V1), maxillary nerve (V2), and mandibular nerve (V3) (Fig. 2.22). The maxillary nerve (V3) has motor function and is monitored with EMG recorded from the masseter.

The facial nerve (CNVII) is one of the most complex of the cranial nerves as well as one of the most often monitored. It has general and special sensory function, parasympathetic function, and motor innervation to the muscles of facial expression. The facial nerve mediates the sense of taste for the anterior two-thirds of the tongue. Also, ironically, CNVII provides parasympathetic innervation to all of the salivary glands except the parotid, which it travels through.

Intraoperative monitoring of the facial nerve function is accomplished with spontaneous and triggered EMG from the muscles of facial expression (Fig. 2.23). There are five branches of the facial nerve (Table 2.2). The mnemonic *T*he *Z*ebra *B*it *M*y *C*ousin can be used to help remember the branches of the facial nerve temporal, zygomatic, buccal, marginal/mandibular, and cervical. It is worth adding that zebras are, in fact, vicious animals and should never be approached. If the intracranial portion of the facial nerve is at risk (such as during a posterior fossa craniotomy), then specific data concerning all branches is not necessary since

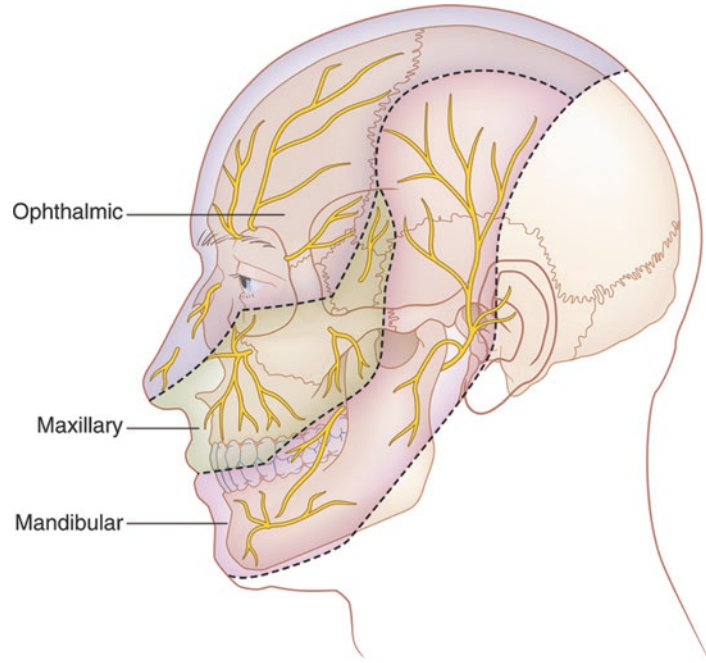


Fig. 2.22 The three branches of the trigeminal nerve and their sensory innervation of the face

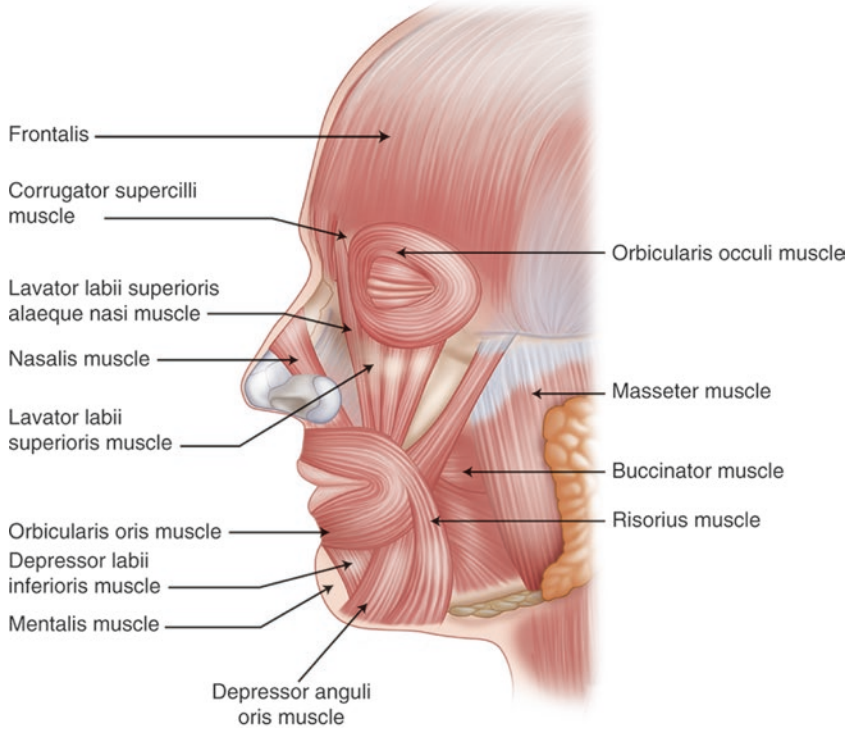


Fig. 2.23 Facial muscles

this point is proximal to the point of branching. Surgery involving the parotid gland, which is at the point of nerve branching, necessitates monitoring all branches of the facial nerve. When equipment limitations compromise the ability to monitor all branches specifically, the marginal/mandibular branch becomes the highest priority to monitor because the fibers that contribute to this branch are located most superficially in the nerve.

The glossopharyngeal nerve (CNIX) is a mixed nerve that receives general sensory fibers from the pharynx, tonsils, and posterior one-third of the tongue. Special sensory fibers mediating taste from the posterior one-third of the tongue are likewise supplied by the glossopharyngeal nerve. This nerve has an autonomic component supplying parasympathetic innervation to the parotid gland. The only somatic motor component of the glossopharyngeal nerve is innervation to the stylopharyngeus muscle. We monitor CNIX by placing electrodes in the soft palate on the ipsilateral side which records far-field responses from the stylopharyngeus muscle.

The vagus nerve (CNX) is the largest parasympathetic nerve of the body. It innervates the thoracic and abdominal viscera, and its autonomic functions are not amenable to intraoperative monitoring. There are two motor branches of the vagus nerve, which supply the intrinsic laryngeal muscles. The superior laryngeal nerve innervates the cricothyroid muscle, while the recurrent laryngeal nerve (RLN) innervates most of the remaining laryngeal muscles. The RLN is so named because of the circuitous route it takes to its termination in the larynx (Fig. 2.24). The RLN

Table 2.2 Branches of the facial nerve

Branch	Mnemonic	Example muscle to monitor
Temporal	The	Orbicularis oculi
Zygomatic	Zebra	Nasalis
Buccal	Bit	Orbicularis oris
Marginal/ mandibular	My	Mentalis
Cervical	Cousin	Platysma

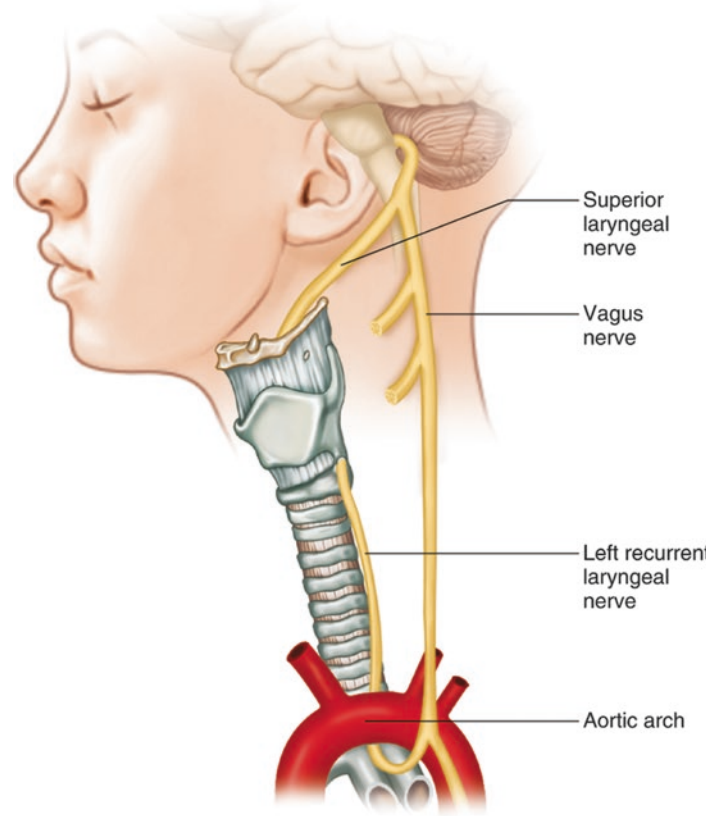


Fig. 2.24 The vagus nerve and its laryngeal branches: recurrent and superior laryngeal nerves

branches from the vagus at high thoracic levels and then loops around the aortic arch (left) or subclavian artery (right) before ascending in the tracheoesophageal groove toward the larynx. The RLN is commonly monitored for anterior cervical fusion surgery, thyroidectomy, and sometimes during carotid endarterectomy. The RLN is also used to monitor the vagus nerve during a posterior fossa craniotomy, as it is the only branch of the vagus that can be monitored.

The spinal accessory nerve (CNXI) innervates two muscles of the neck, namely, the trapezius and sternocleidomastoid. The spinal accessory is purely a motor nerve. The last cranial nerve we will consider is also a motor nerve. The hypoglossal nerve (CNXII) provides motor innervation to the tongue and is important for aiding speech and swallowing. Placing electrodes in the ipsilateral side of the tongue is the method for monitoring the hypoglossal nerve.

Neurovasculature

An extensive network of blood vessels perfuses the brain. The neurovasculature can be divided into anterior and posterior circulations. A series of communicating arteries bridge the circulation from anterior to posterior as well as the left and right. These interconnecting vessels facilitate *collateral circulation* throughout the brain and collectively make up the structure known as *the circle of Willis* (Fig. 2.25). Collateral circulation is the flow of blood through alternate pathways when the main blood vessel is functionally impaired. People with good collateral flow are often able to tolerate ischemic events more readily than those without adequate collateral flow. Only a minority of humans have a complete circle of Willis. A majority have some variation of an incomplete circle of Willis. An understanding of brain perfusion is essential to the neuromoni-

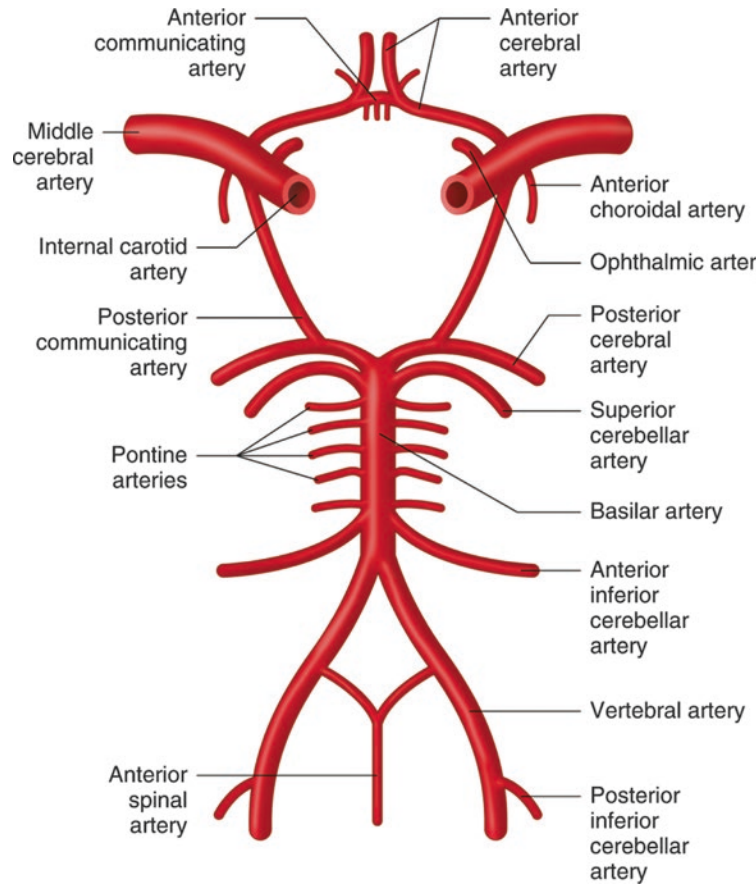


Fig. 2.25 The circle of Willis

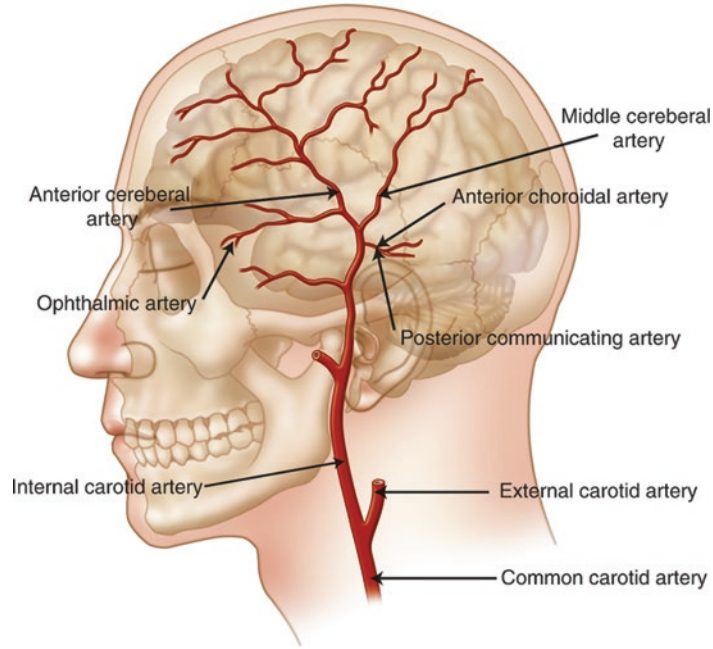


Fig. 2.26 Anterior cerebral circulation

toring clinician, as you will be called upon to correlate changes in electrical potentials to the anatomic location and the blood supply in order to make accurate real-time interpretations of your data.

The anterior circulation is supplied by the paired internal carotid arteries (ICA) and is responsible for perfusion of the majority of the cerebral cortex (Fig. 2.26). The right and left internal carotids enter the base of the brain and bifurcate into the middle cerebral artery (MCA) and anterior cerebral artery (ACA). The MCA supplies the lateral aspects of the cerebral hemispheres including the hand and face areas of the sensory and motor homunculi. The vascular territory of the ACA includes the medial most aspects of the cerebral hemispheres including areas of the sensory and motor homunculi that represent the lower extremity and genitalia. The left and right anterior circulations are connected via the anterior communicating artery.

A lesion in the vascular territory of the MCA will result in sensorimotor deficits in the contralateral face and upper extremity. The deficits are contralateral because the sensory and motor pathways affected are crossed pathways. We will discuss this in greater detail later. An ACA territory lesion results in sensorimotor deficits in the contralateral lower extremity. These cerebral functional areas are best monitored by the upper and lower extremity sensory and motor evoked potentials.

Cerebral areas supplied by overlapping terminal branches of both the MCA and ACA are known as watershed areas. These areas have reduced blood flow compared to the rest of the vascular territory and, as such, are more vulnerable to reductions in blood flow. The watershed areas are the most frequent site of stroke, comprising approximately 10% of all strokes. Strokes in this area are termed *watershed infarcts*.

The posterior circulation is supplied by the vertebrobasilar complex consisting of the vertebral and basilar arteries and their branches (Fig. 2.27). The posterior circulation supplies the occipital lobes of the brain, subcortical structures such as the thalamus, and the brainstem and cerebellum. A pair of vertebral arteries arising from the subclavian arteries ascends through the transverse foramina of the cervical vertebrae before joining at midline to form the basilar artery. The anterior spinal artery is given off from the vertebral arteries and supplies the anterior two-thirds of the spinal cord. There is only one anterior

spinal artery, but it receives contributions from both the left and right vertebral arteries.

The largest branch of the vertebral artery is the posterior inferior cerebellar artery (PICA), which is one of the three main blood vessels supplying the cerebellum. The two other main cerebellar arteries are the anterior inferior cerebellar artery (AICA) and the superior cerebellar artery (SCA), both are branches of the basilar artery. Branching from the left and right PICA are the two posterior spinal arteries, which supply the posterior one-third of the spinal cord. Together with the anterior spinal artery mentioned earlier, these arteries contribute significantly to spinal cord perfusion (Fig. 2.28). We will discuss some additional features of spinal cord perfusion in "The Spinal Cord" section of this chapter.

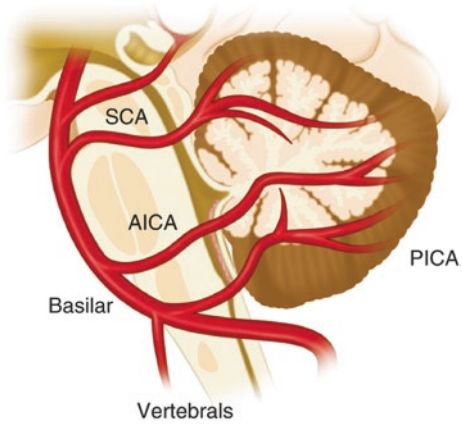


Fig. 2.27 Lateral view of the brainstem and cerebellum illustrating the posterior circulation. (SCA superior cerebellar artery, PICA posterior inferior cerebellar artery, AICA anterior inferior cerebellar artery)

The labyrinthine artery is an important branch of AICA providing blood to the cochlea. Compromise of the labyrinthine artery results in a cochlear stroke and loss of hearing as well as all waves of the brainstem auditory evoked potential.

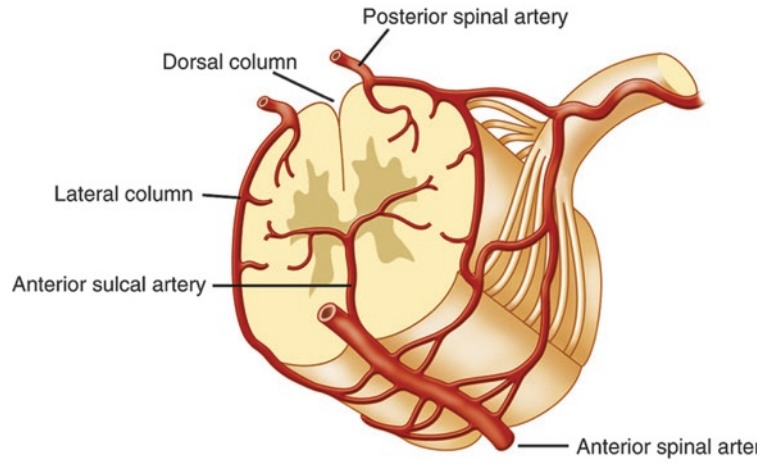
The basilar artery terminates into the left and right posterior cerebral arteries, which supply blood to the occipital lobes, the medial aspects of the temporal lobes, and the midbrain. Two posterior communicating arteries arise from the posterior cerebral artery and provide a connection to the anterior circulation thus completing the circle of Willis.

Deficits resulting from lesions of the vertebrobasilar system range from cranial nerve palsies and autonomic dystonia to sensorimotor symptoms such as quadriparesis. Intraoperative monitoring changes that may indicate posterior ischemia include critical changes in brainstem auditory evoked potentials, motor evoked potentials, or somatosensory evoked potentials. Thalamic and brainstem-generated potentials are particularly likely to be reduced in amplitude.

The Spinal Column

The spinal column provides protection of the spinal cord and allows for movement of the torso. Made up of 33 bones, called vertebrae, the spine is both incredibly protective and flexible.

Fig. 2.28 Spinal cord arterial circulation



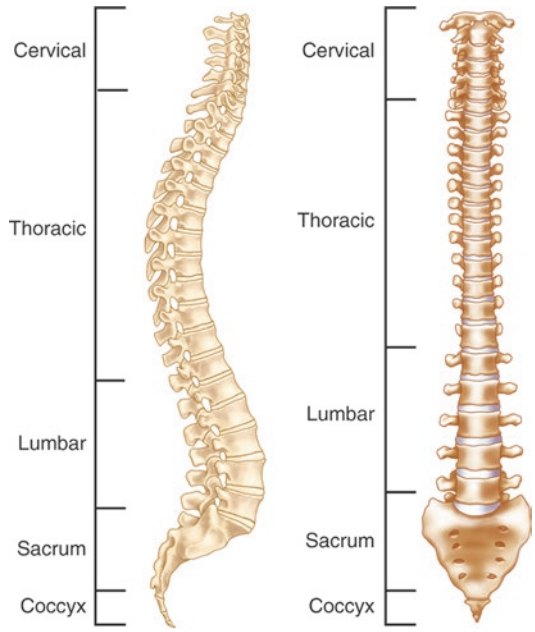


Fig. 2.29 Lateral and posterior view of the vertebral column and its divisions

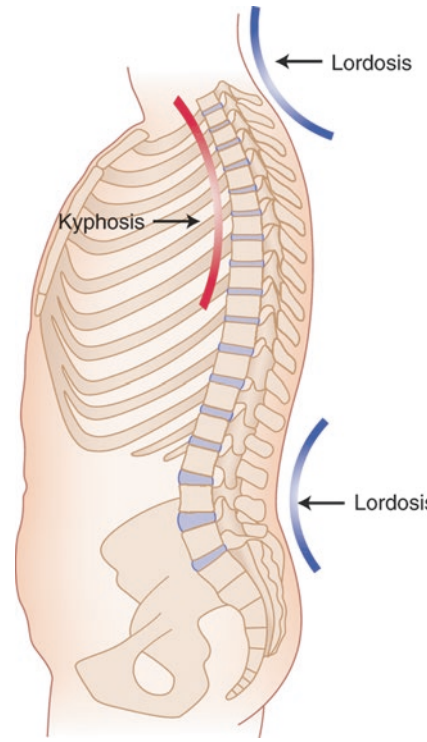


Fig. 2.30 Normal curvatures of the spine

The spinal column is divided into segments. The cervical, thoracic, and lumbar segments are comprised of individual vertebra separated by intervertebral discs allowing for movement. The sacral and coccygeal segments of the spinal column are comprised of fused vertebrae and are immobile. Of the 33 total vertebrae, 7 are cervical, 12 thoracic, 5 lumbar, 5 fused sacral, and 4 fused coccygeal (Fig. 2.29). Most of the vertebrae contain a *body* sometimes called the centrum. A *vertebral arch* formed by the left and right *pedicles* and a *lamina* enclose a space known as the *vertebral canal*, also called the spinal canal. The vertebral canal contains the spinal cord or nerve roots depending on the level.

Curvatures of the Spine

In a normal spine, there are curvatures, which are important for helping the spine perform its functions of providing balance, movement, and the distribution of loads. Cervical and lumbar concavities are termed lordosis, while thoracic and sacral convexities are termed kyphosis (Fig. 2.30). During fetal development and for a period of time during infancy, the spine is curved in a "C" shape, which is kyphotic. The secondary lordotic curves develop as the child begins to hold his head up and eventually walk and is a result of increased musculature and increased load bearing on the spine. The cervical lordosis and thoracic kyphosis have a normal range of between 20 and 40°, and the lumbar lordosis ranges from 40° to 60°. Curvatures in excess of this range are considered abnormal, and the patient is then said to be "kyphotic" or "lordotic."

An abnormal lateral curvature of the spine (greater than 10°) is known as scoliosis (Fig. 2.31). Scoliosis can either be idiopathic, having no known cause, or a result of a neuromuscular disease. Most cases of scoliosis are idiopathic. Neuromuscular scoliosis may be part of a larger syndrome that involves other body systems. Scoliosis tends to progress as a child ages and can begin to interfere with the

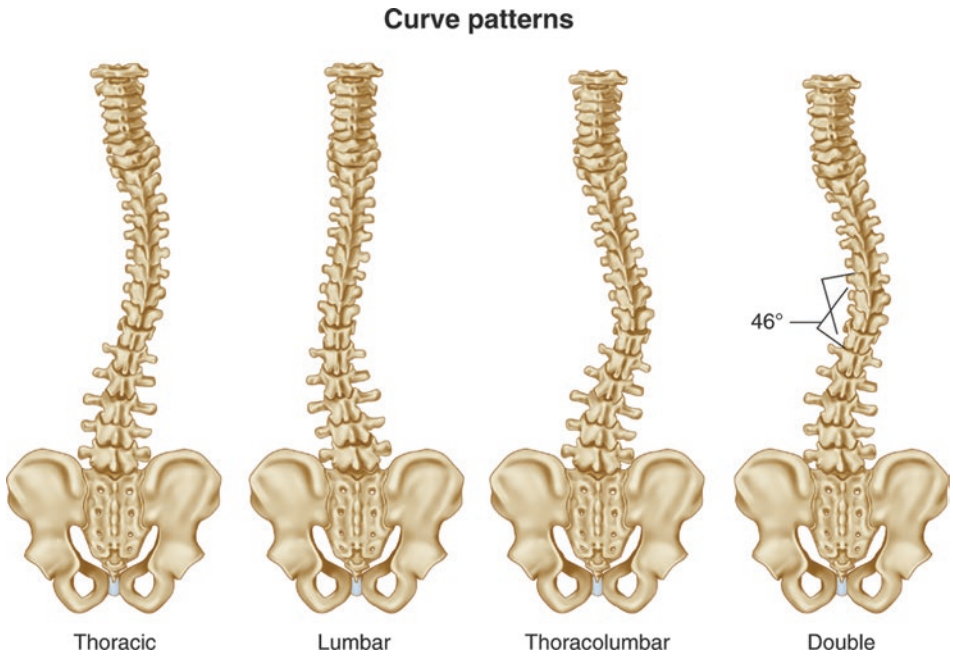


Fig. 2.31 Commonly seen curve patterns in patients with scoliosis

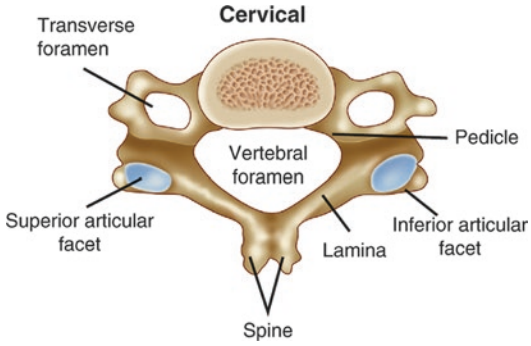


Fig. 2.32 A typical cervical vertebra seen between C3 and C6

vital capacity, the ability to breathe. Surgical intervention is often required for spinal deformities such as scoliosis. The outcomes for spinal deformity surgery have improved since the advent of intraoperative neurophysiologic monitoring.

Cervical Vertebrae

The cervical vertebrae are the smallest of all the vertebral types and allow for maximal movement. The cervical vertebrae are distinguished by some unique characteristics common to C3–C6 (Fig. 2.32). There are three distinct cervical vertebrae—C1, C2, and C7—which we will consider separately.

General Characteristics of C3–C6

In addition to their small and flattened bodies, each cervical vertebra has a pair of foramina located in the transverse processes. These *transverse foramina* contain the vertebral artery, vein, and sympathetic nerve plexus. The spinous processes of these vertebrae are bifid with one side usually larger than the other. The pedicles of the cervical vertebrae are small and project posterolaterally. The vertebral canal contains the spinal cord, while the intervertebral foramen, formed by the articulation of two vertebrae, is the exit point for the spinal nerves.

Special Cervical Vertebrae (C1, C2, and C7)

The C1 vertebra has the name *atlas* after the Greek mythological god that carried the world on his shoulders. You may therefore guess that atlas joins the skull with the spine. The atlas has no

body but rather is a ring consisting of an anterior and posterior arch. C1 fuses with the body of C2, the axis (Fig. 2.33a).

The C2 vertebra is named *axis* for the fact that it provides an axis of rotation for C1. Its most prominent feature is the bony projection known as the dens. The dens is also called the odontoid process since it resembles a tooth (Fig. 2.33b). The union between C1 and the occiput is the atlanto-occipital joint which is responsible for the nodding movement of the head. The C1–C2 joint is also known as the atlanto-axial joint and provides for rotation of the head on the neck.

The C7 vertebra has a prominent spinous process and therefore is named *vertebra prominens*. Occasionally C7 has an abnormal pair of ribs associated with it that can cause compression of blood vessels as well as the nerves of the brachial plexus. This condition, known as *thoracic outlet syndrome*, can cause pain, numbness, and tingling in the upper extremity.

Thoracic Vertebrae

The thoracic segment of the vertebral column is the least flexible due to the attachment of the ribs. The ribs attach to facets located on both the vertebral body and the transverse processes. These facets are called *costal facets*. The bodies of the thoracic vertebrae are larger than the cervical but smaller than the lumbar (Fig. 2.34). The size increases with progression from T1 to T12. The vertebral canal contains the spinal cord, and the intervertebral foramina remain the exit points for the spinal nerves.

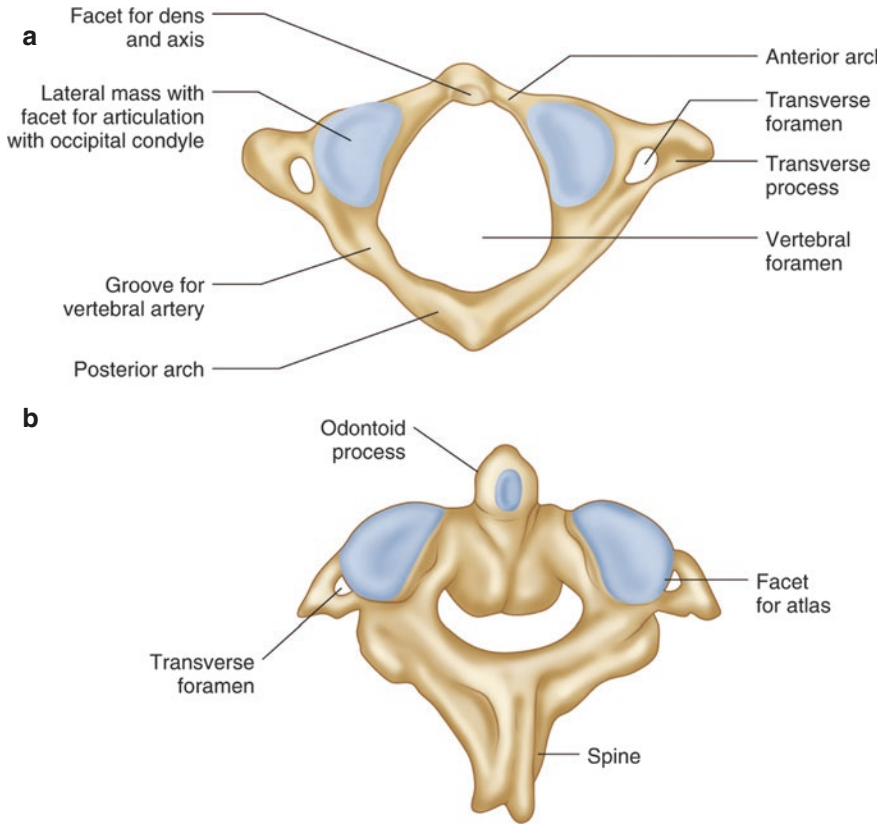


Fig. 2.33 (**a**) The C1 vertebra, atlas. (**b**) The C2 vertebra, axis

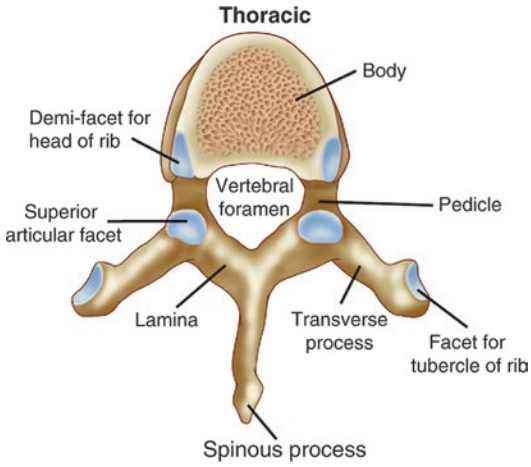


Fig. 2.34 A typical thoracic vertebra

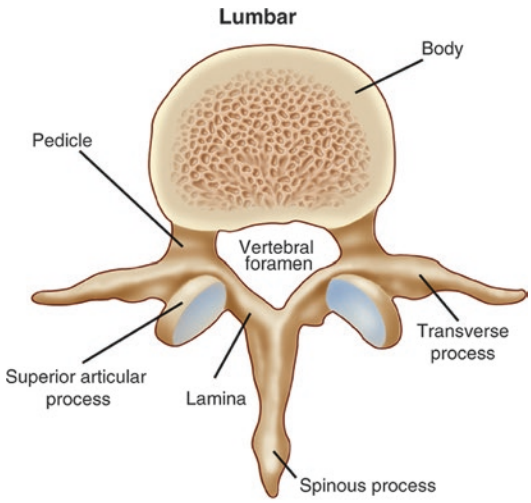


Fig. 2.35 A typical lumbar vertebra

Lumbar Vertebrae

The five lumbar vertebrae are the largest in size and are characterized by the absence of both transverse foramina and costal facets (Fig. 2.35). The spinal cord usually ends at vertebral level L1. At levels caudal to L1, the lumbar and sacral nerve roots occupy the vertebral canal as they descend toward their respective vertebral levels to exit. At the most rostral lumbar segments, there are more nerve roots occupying the vertebral canal. As you progress toward L5 the number of nerve roots in the canal diminishes as they begin to exit the vertebral column (Fig. 2.36). The lumbar region of the spine is highly mobile and is responsible for bearing the most compressive

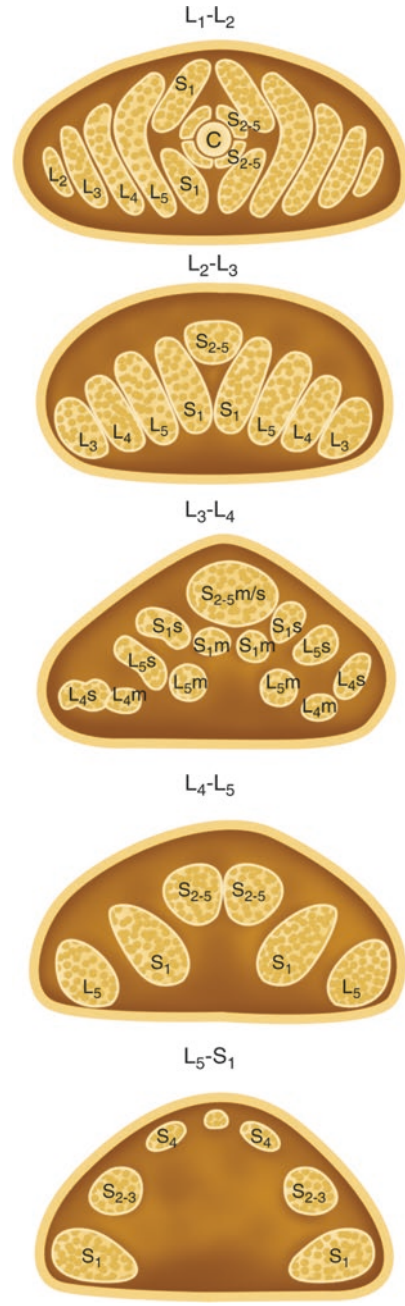


Fig. 2.36 Serial cross-sections through the cauda equina showing the decreasing number of nerve roots remaining as you approach lower lumbar and sacral vertebral levels

load. For this reason, the lumbar region is also the most vulnerable to injury. Of all the lumbar vertebrae, L5 is the most common site of injury and disease.

The Sacrum and Coccyx

The *sacrum* is a large triangular-shaped bone that is comprised of five fused sacral vertebrae. The sacrum fits like a wedge in between the two hipbones of the pelvis. Inferior to the sacrum is the *coccyx* or tailbone, which is comprised of four fused coccygeal vertebrae.

The Spinal Cord

The spinal cord is part of the central nervous system extending from termination of the medulla oblongata to approximately the L1 vertebral level. The function of the spinal cord is to transmit sensory and motor information to and from the brain and periphery. Like the vertebral column, the spinal cord is divided into cervical, thoracic, lumbar, sacral, and coccygeal levels. The cervical cord is divided into eight segments even though there are only seven cervical vertebrae. There are 12 thoracic segments, 5 lumbar segments, 5 sacral segments, and 1 coccygeal segment. Each spinal cord segment gives rise to a pair of spinal nerves for a total of 31 pairs of spinal nerves.

The spinal cord is larger in diameter at the cervical and lumbar levels due to the increased number of cell bodies and nerve fibers dedicated to the innervation of the limbs. These areas are known as the *cervical and lumbar enlargements* (Fig. 2.37).

The spinal cord is contained within the dural sac, often called the *thecal sac*, and is bathed by cerebral spinal fluid. The spinal cord is anchored at its caudal end to the thecal sac by an extension of the pia mater called the *filum terminale* (see Fig. 2.37). The filum terminale internum anchors

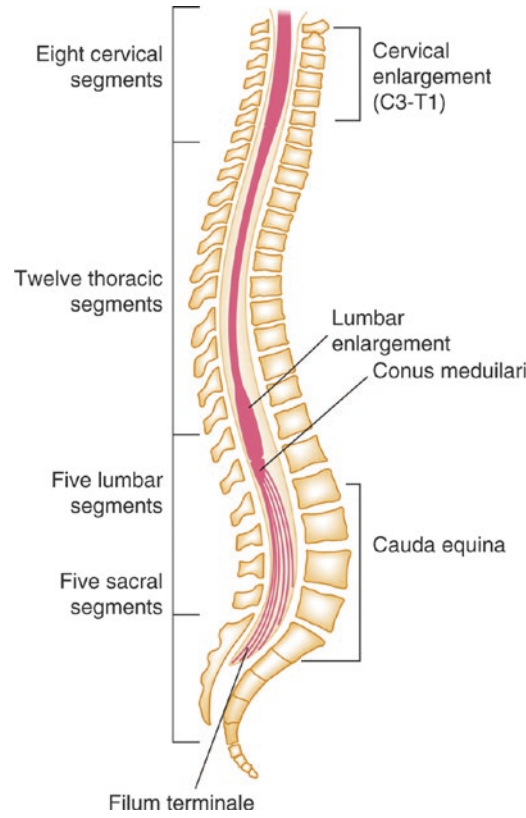


Fig. 2.37 The spinal cord showing the lumbar and cervical enlargements, conus medullaris, and filum terminale

the spinal cord to the interior surface of the dural sac. The filum terminale externum is the continuation of the filum internum, which anchors the dural sac to the coccyx.

The spinal cord ends at about the L1 vertebral level in a tapered structure known as the *conus medullaris* (see Fig. 2.37). The conus medullaris contains the lower lumbar and sacral spinal cord segments. Surgery near the L1 vertebral level, therefore, places sacral function at risk due to the proximity of the conus. For this reason, the external anal sphincter should be monitored for procedures at T12 or L1 vertebral levels. Injury to the conus medullaris will result in nerve palsies of the lumbosacral plexus including deficits in bowel and bladder control. Sexual function may also be compromised.

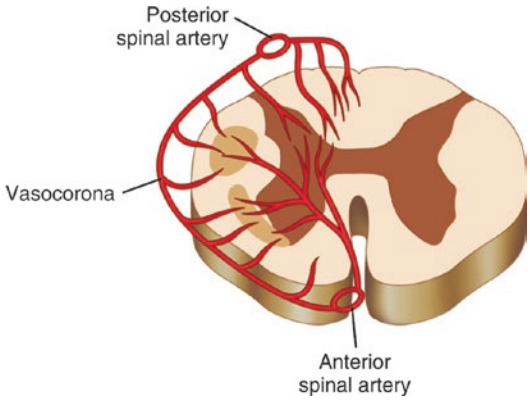


Fig. 2.38 The vasocorona is an anastomosis between the anterior and posterior spinal arteries

Spinal Cord Vasculature

Three longitudinal arteries arising from the posterior cerebrovasculature (as discussed earlier) perfuse the spinal cord. There is collateral circulation among these three arteries via anastomoses. These anastomoses form the *vasocorona* (Fig. 2.38). In addition to the three longitudinal arteries, each spinal cord level is fed by the anterior and posterior radicular arteries, which enter the cord along the nerve roots. The word *radicular* means nerve root. The radicular arteries have anastomoses with each other providing collateral flow. The anterior radicular arteries contribute to the vascular territory of the anterior spinal artery, and the posterior radicular arteries contribute to the vascular territory of the two posterior spinal arteries. The largest anterior radicular artery is known as the *artery of Adamkiewicz* (Fig. 2.39). This artery is highly variable and, in most people, arises from the aorta on the left side at low thoracic or high lumbar vertebral segments. This artery bolsters the perfusion of the anterior two-thirds of the lumbar and sacral segments of the spinal cord. The artery of Adamkiewicz may be placed at risk during surgical procedures of the lower thoracic region, especially those that utilize a lateral approach or involve interruption of the radicular blood supply. Provocative testing with motor evoked potentials is used to monitor perfusion of the spinal cord and help determine whether a particular radicular vessel can be sacrificed or temporarily clamped.

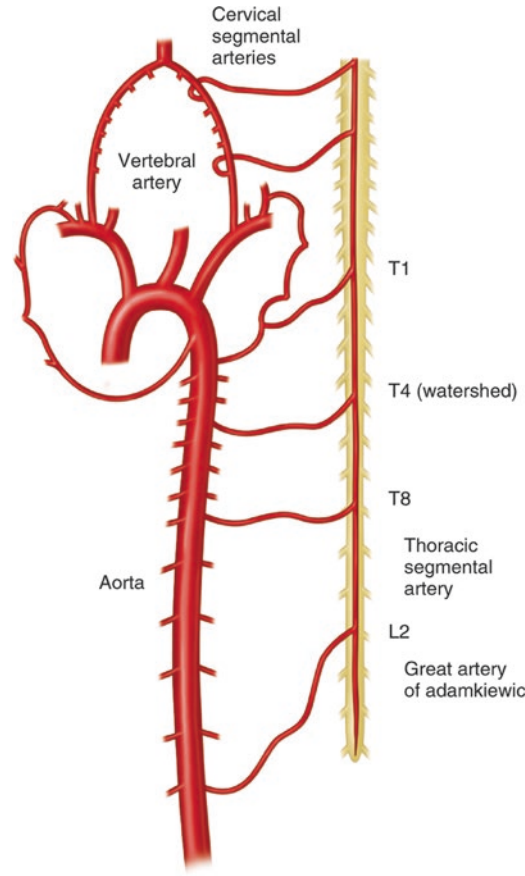


Fig. 2.39 Segmental arteries coming off of the aorta. The artery of Adamkiewicz is shown emerging from the aorta adjacent to the upper lumbar spinal cord segments

Internal Organization of the Spinal Cord

A cross-section through the human spinal cord reveals white matter in the periphery surrounding a butterfly-shaped gray matter in the center. A central canal continuous with the ventricles of the brain contains CSF. Figure 2.40 illustrates the white matter organization of the spinal cord. The gray matter is organized into ten functional layers known as Rexed's laminae (Fig. 2.41).

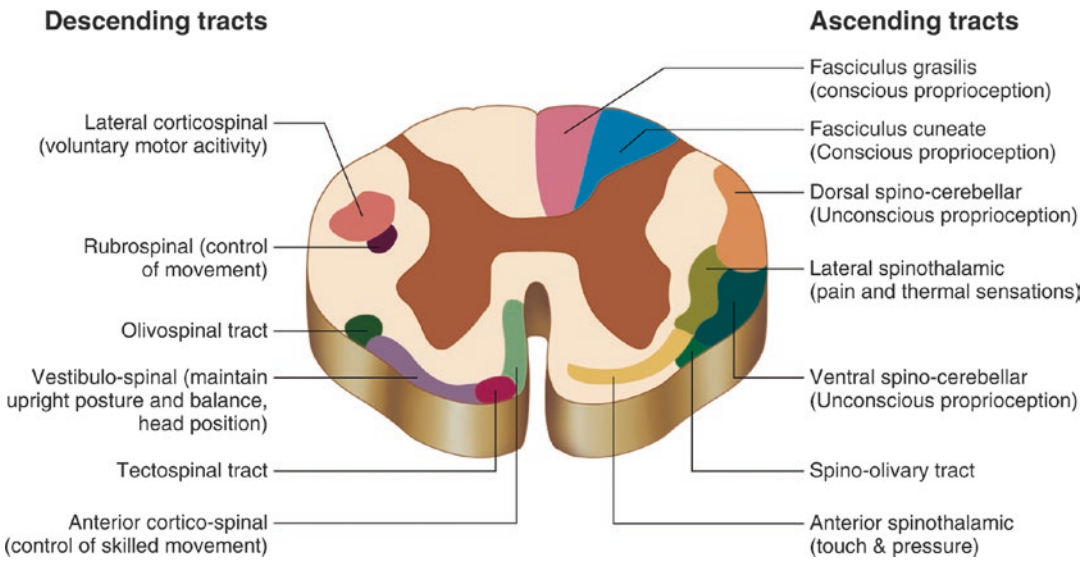


Fig. 2.40 A cross-section through the spinal cord showing the white matter organization. Descending tracts (motor) are illustrated on the *left* while ascending tracts (sensory) are illustrated on the *right*

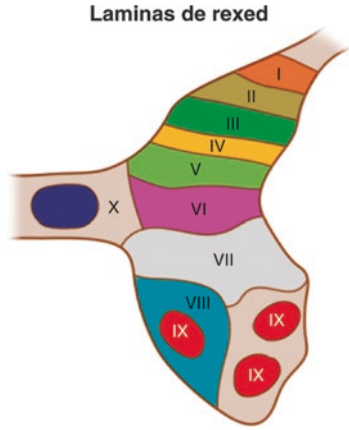


Fig. 2.41 Organization of the spinal cord gray matter into Rexed's laminae

There are several areas of particular importance to the neuromonitoring clinician. The dorsal columns carry specific sensory information from the periphery to the brain. As we will discuss later, the dorsal columns are further divided into smaller white matter tracts or *fasciculi*. The dorsal columns are part of the dorsal column medial lemniscal pathway that is monitored with somatosensory evoked potentials. Another important area of white matter is the corticospinal tract which is responsible for voluntary movement and is monitored using motor evoked potentials.

Rexed's laminae IX and X contain neuronal cell bodies that are also part of the corticospinal tract. These neurons are contained within the ventral portion of the spinal cord gray matter, an area often called the *ventral horn*.

Spinal Nerves

Each segment of the spinal cord gives rise to a pair of spinal nerves, 31 total. Each spinal nerve is a mixed nerve comprised of a dorsal (sensory) root and ventral (motor) root (Fig. 2.42).

The dorsal root brings sensory information from the periphery into the spinal cord. Neurons that make up the dorsal root have their cell body located in a structure known as the dorsal root ganglion (DRG). There are paired DRG at each spinal cord segment. Neurons of the DRG are of the pseudo-unipolar morphological type. Pseudo-unipolar neurons have one process that bifurcates into two: a central and peripheral process. The peripheral process terminates in a

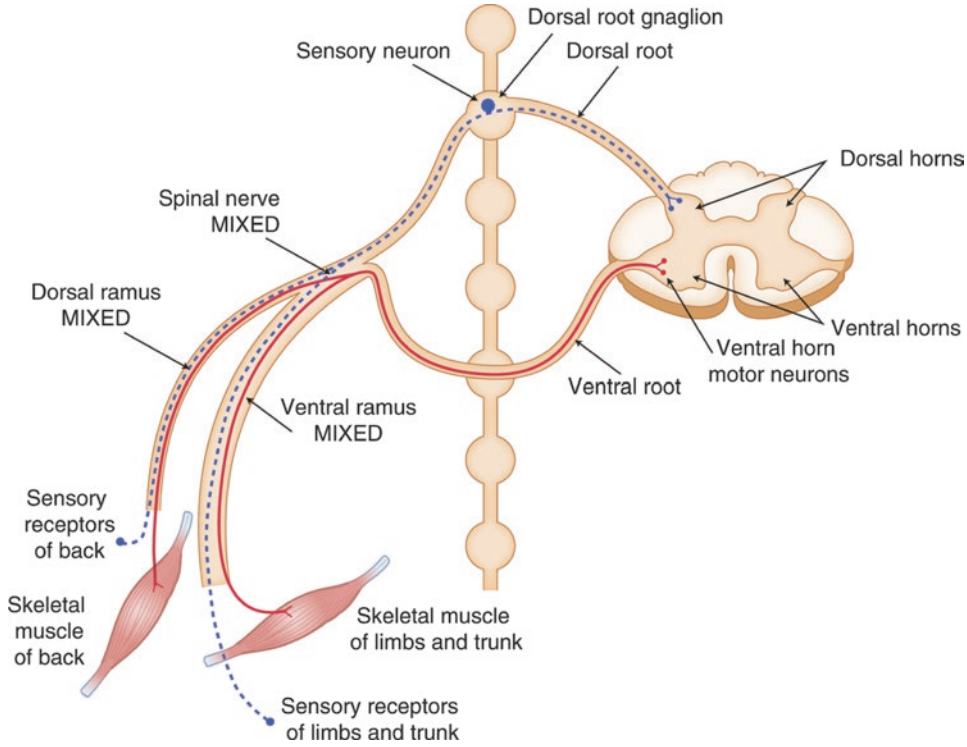


Fig. 2.42 Organization of spinal nerves

peripheral target and has a sensory receptor at its ending. The sensory receptor recognizes specific sensory modalities. The central process of neurons in the DRG enters the spinal cord through the dorsal root.

The ventral root of the spinal nerve carries motor information from the spinal cord to the periphery. Neurons located in the ventral horn send their axons out via the ventral root. The dorsal and ventral roots join to form the spinal nerve before exiting the vertebral column via the intravertebral foramen. Monitoring the nerve roots during surgery is one of the functions of IOM. The dorsal root has been monitored using dermatomal SSEPs, but this technique has been largely replaced by using EMG to monitor the ventral roots.

Neural Pathways

The function of the nervous system can be monitored intraoperatively by stimulating and recording from opposite ends of neural pathways. Stimulating sensory pathways distally and motor pathways proximally while recording from the opposite ends can determine the integrity of an entire neural pathway.

In order to both design the monitoring plan and accurately interpret the data, the monitoring clinician must have a detailed understanding of the neural pathway being tested. We will discuss two pathways in this section: the *dorsal column medial lemniscal tract* (DCML) and the *corticospinal tract* (CST). It is critical that IOM clinicians be familiar with both of these pathways. There are many other neural pathways that are not directly tested with IOM techniques, and as such, they will not be considered in this volume.

DCML Pathway

The DCML pathway is a sensory pathway mediating the sensory modalities of deep touch, vibration, conscious proprioception, two-point discrimination, and stereognosis (recognition of texture). Occupying part of the dorsal white matter of the spinal cord, this pathway lies in the vas-

cular territory of the posterior spinal arteries. The DCML pathway is monitored using SSEPs as a means of protecting the spinal cord during surgery. A detailed knowledge of the DCML pathway is required for accurate monitoring of SSEP data during surgery.

There are three neurons of the DCML pathway. The first-order neuron has its cell body in the dorsal root ganglion. Sensory information encoded by specialized nerve endings moves along the peripheral process of the first-order neuron and then to the spinal cord via the central process traveling with other fibers of the dorsal root of the spinal nerve.

The medial division of the dorsal columns is called the *fasciculus gracilis*. The fasciculus gracilis carries information entering the spinal cord from the lower thoracic, lumbar, and sacral spinal nerves. Sensory information from the upper thoracic and cervical regions enter the spinal cord and ascend in the *fasciculus cuneatus*, the lateral division of the dorsal columns. There is a medial to lateral topography of the dorsal columns with sensory information from the lower extremity medial and the upper extremity lateral. This is similar to the homuncular organization of the primary somatosensory cortex.

The axons of the dorsal columns continue to ascend in the spinal cord without synapsing until they reach the caudal medulla and synapse in the *dorsal column nuclei*. There are two pairs of dorsal column nuclei: nucleus gracilis and nucleus cuneatus. The dorsal column nuclei contain the cell bodies of the second-order neurons of the DCML pathway. Fibers from the fasciculus gracilis synapse in the nucleus gracilis, while fibers traveling in the nucleus cuneatus synapse in the nucleus cuneatus.

The second-order neurons of the dorsal column nuclei send their axons, named *internal arcuate fibers*, out and across the midline to ascend in the brainstem as a white matter tract called the *medial lemniscus*. The crossing over of white matter tracts is called a decussation. The fibers of the DCML pathway cross at a point called the *sensory decussation*. The medial lemniscus now contains fibers from the contralateral side of the body. The medial lemniscus ascends through the pons and midbrain on its way to the thalamus, where its fibers will synapse on the third-order neurons of the DCML pathway.

The thalamus is a multinucleated deep brain structure that relays sensory information from the periphery to the cortex. The nucleus of the thalamus that receives input from the DCML pathway is the ventroposterolateral nucleus of the thalamus (VPL). Fibers of the medial lemniscus terminate in the VPL on the third-order neurons of the DCML pathway. Axons leaving the VPL ascend through the internal capsule and are known as the *thalamic radiations*. These fibers next synapse in the primary somatosensory cortex located on the postcentral gyrus. Axons carrying sensory information from the lower extremity synapse more medially than axons carrying information from the upper extremities. The DCML pathway is shown in detail in Fig. 2.43.

Corticospinal Tract

The *corticospinal tract* is a motor pathway that mediates voluntary movement of the limbs and trunk, often called the *pyramidal tract*, because its fibers create surface features in the medulla known as the pyramids. There are two neurons in this pathway: an *upper motor neuron* and a *lower motor neuron* (Fig. 2.44). The upper motor neuron resides in layer V of the primary motor cortex located in the precentral gyrus. You should recall the homuncular organization of the precentral gyrus. The lower motor neuron, also called the alpha motor neuron, is located in the ventral horn of the spinal cord gray matter.

Voluntary motor control is initiated at the level of the upper motor neuron. Axons of the upper motor neurons pass through the internal capsule and descend through the midbrain and pons before reaching the medulla. In the caudal medulla, approximately 80% of the fibers decussate in an area known as the pyramidal or motor decussation. The crossed fibers and a small percentage of the uncrossed fibers contribute as the lateral corticospinal tract and synapse on lower motor neurons that innervate distal musculature. Most of the fibers that

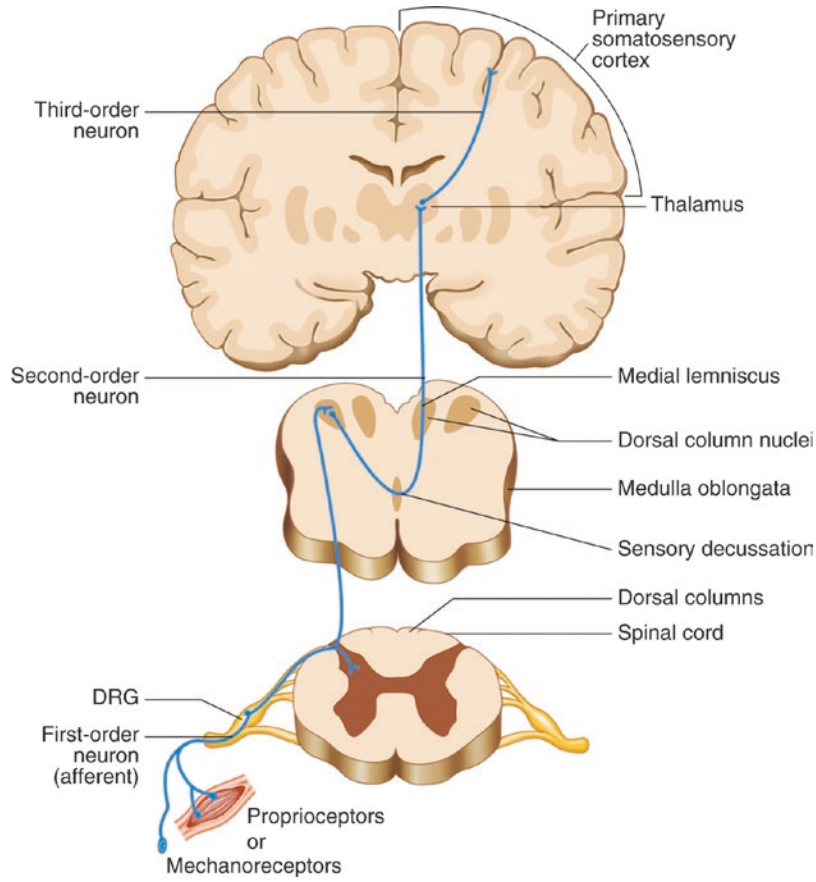


Fig. 2.43 The dorsal column medial lemniscal (DCML) pathway

remain uncrossed at the level of the pyramidal decussation continue as the anterior corticospinal tract. These fibers generally cross near the level where they synapse. They synapse on lower motor neurons that innervate the proximal musculature.

The lower motor neurons are tonically inhibited by both descending inputs and afferent input from the musculature. Such tonic inhibition provides a mechanism for control over the skeletal muscles. Descending inputs from the upper motor neurons of the CST synapse on the alpha motor neurons and, if the input is sufficient, bring them to threshold causing an action potential. These action potentials travel along axons running in the ventral root and join the spinal nerve and peripheral nerves on their way to the target skeletal muscle.

Nerve Plexuses

A nerve plexus is an interconnecting group of nerves, innervating the same area of the body. Branches of a nerve plexus may join to become one or more larger peripheral nerves. The somatic peripheral nervous system contains the cervical, brachial, lumbar, and sacral plexuses. Intraoperative monitoring clinicians will encounter the brachial, lumbar, and sacral plexuses most often in their practice.

Brachial Plexus

The brachial plexus is a network of interconnecting ventral rami from spinal nerves C5–T1 that innervates the arm, forearm, and hand.

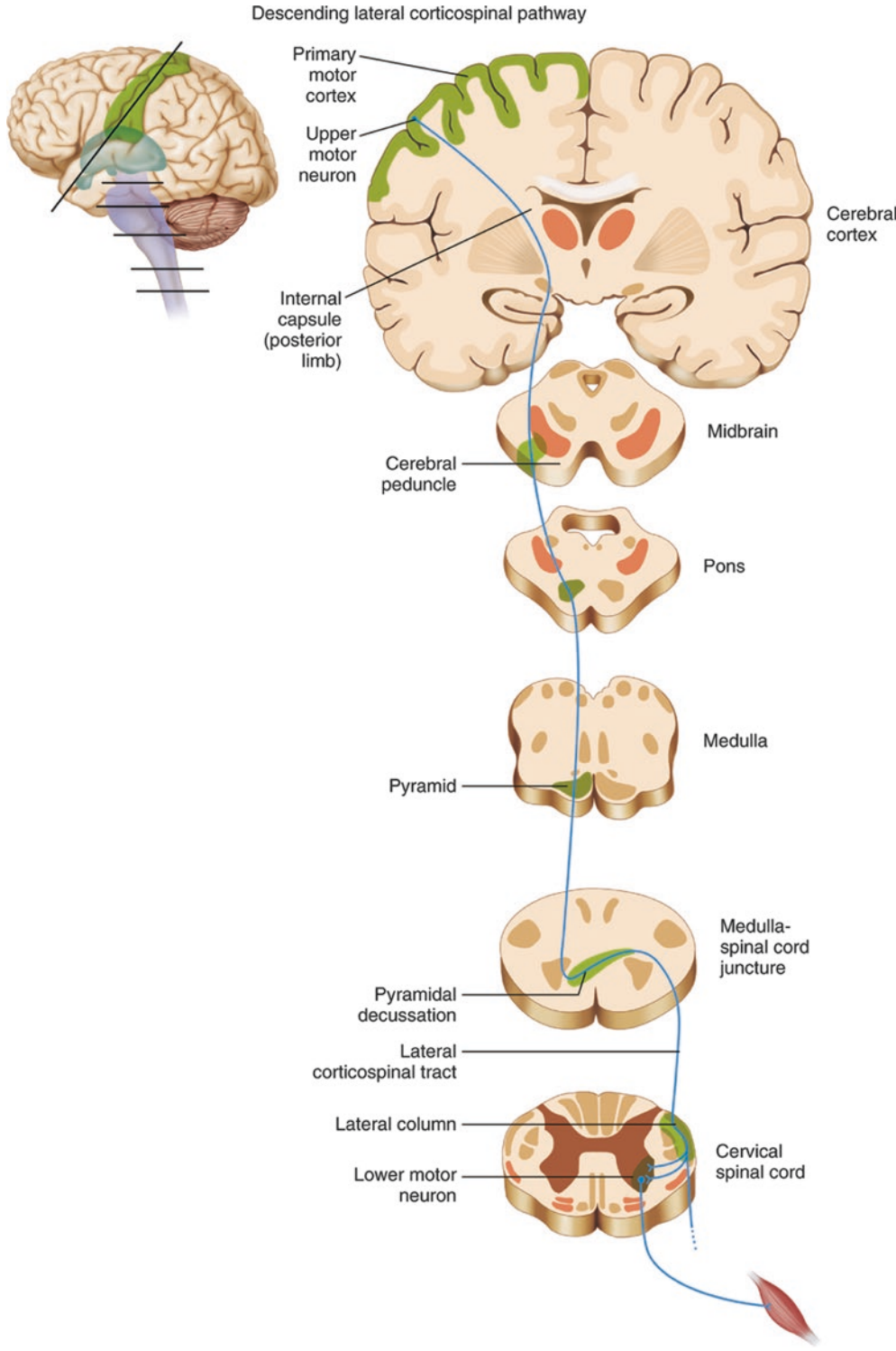


Fig. 2.44 The corticospinal tract

Note: The term ventral ramus is not synonymous with the term ventral root! After the dorsal and ventral roots join to form the spinal nerve, there is a bifurcation into a dorsal and ventral ramus. The dorsal rami of spinal nerves innervate skeletal muscles of the back, while the ventral ramus innervates skeletal muscles of the trunk and limbs (see Fig. 2.42*).*

The brachial plexus proceeds out of the neck into the upper limb and is organized around the axillary artery. The ventral rami of spinal nerves C5–T1 form the *roots* of the brachial plexus. These roots further organize into *trunks* and then into *divisions* and *cords* of the brachial plexus before ending in terminal branches, which are the individual peripheral nerves innervating the upper limb (Fig. 2.45).

The individual roots merge into three trunks: the upper trunk (C5–C6), middle trunk (C7), and lower trunk (C8–T1). Each of the trunks splits into an anterior and posterior division for a total of six divisions. These six divisions will regroup into three cords named according to their position relative to the axillary artery.

The posterior cord (lying posterior to the axillary artery) is comprised of the three posterior divisions and contains roots C5–T1. The lateral cord contains the anterior divisions of the upper and middle trunks and contains roots C5–C7. The medial cord is a continuation of the anterior division of the lower trunk and contains roots C8–T1.

There are many terminal branches to the brachial plexus, and in time you may need to familiarize yourself with all of them. For most IOM clinicians, however, being familiar with five is sufficient. The five terminal branches that provide motor innervation to the muscles of the upper limb are the following nerves: median, ulnar, radial, axillary, and musculocutaneous. Table 2.3 contains information on the nerves of the brachial plexus.

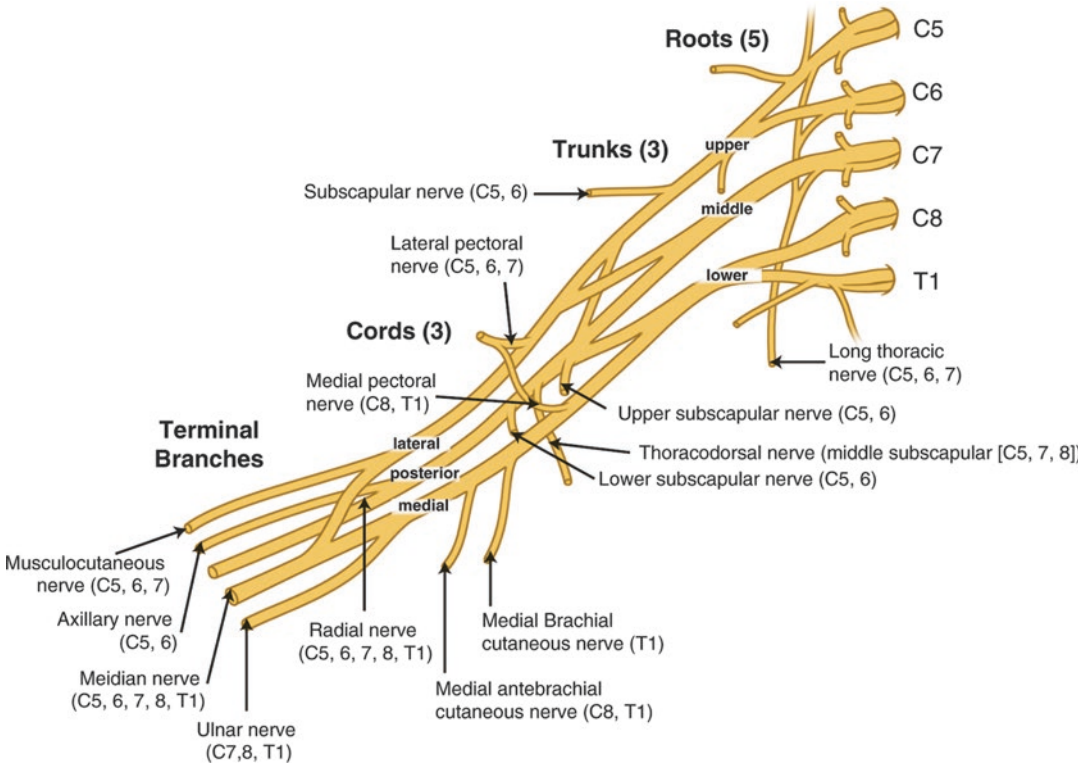


Fig. 2.45 The brachial plexus

Table 2.3 Nerves of the brachial plexus

Nerves	Segment	Muscles	Motion	Sensation
Long thoracic	C5, 6, 7	Serratus anterior	Winged scapula	–
Supraclavicular	C5, 6	Supraspinatus	Shoulder abduction	–
Axillary	C5, 6	Deltoid	Arm abduction	Lateral arm below the shoulder
Musculocutaneous	C5, 6, 7	Biceps and brachialis	Elbow flexion	Lateral forearm
Redial	C5–T1	Extensor carpi radialis longus and brevis	Extension of elbow and wrist	Posterior, lateral arm Dorsum of hand
Median	C5–T1	Pronator teres and quadratus Flexor carpi radialis Flexors of fingers	Flexion of wrist and fingers	Radial palm Palmer surface Tips of lateral 3½ fingers
Ulnar	C8–T1	Interossei and lumbricals Adductor pollicis	Movement of medial 2 fingers	Ulnar and dorsal palm Medial 1½ fingers

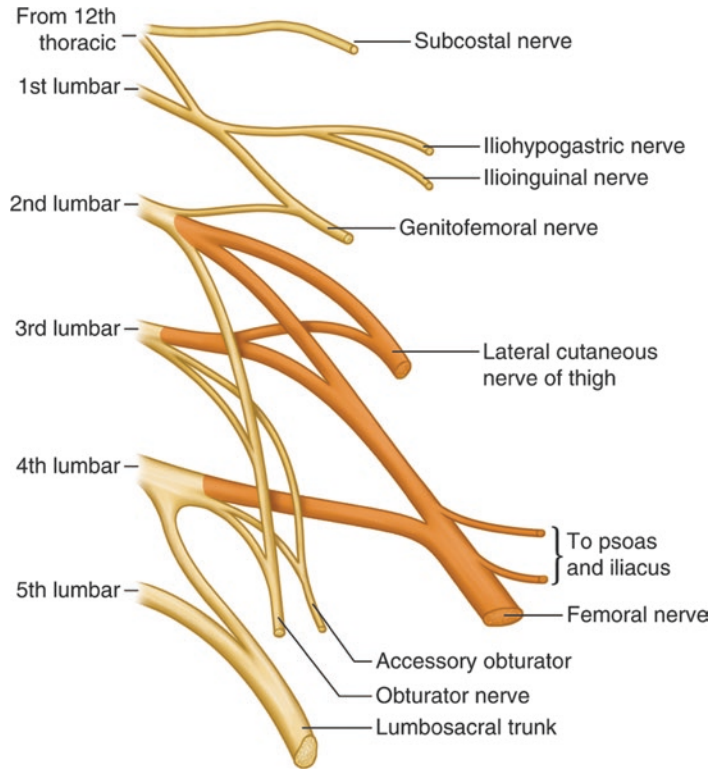


Fig. 2.46 Lumbar plexus

Lumbosacral Plexus

The anterior rami of the lumbar and sacral spinal nerves form a plexus that gives rise to the nerves of the lumbosacral plexus innervating the lower extremity and pelvis. It is convenient, however, to consider the lumbar and sacral plexuses separately.

The Lumbar Plexus

The *lumbar plexus* receives contribution from the ventral rami of spinal nerves L1–L4 with input from the subcostal nerve (T12) as well. The *lumbosacral trunk*, containing part of the L4 nerve and all of the L5, connects the lumbar and sacral plexuses (Fig. 2.46).

Table 2.4 Branches of the lumbar plexus

Nerve	Segment	Muscle	Motion	Sensation
Iliohypogastric	T12–L1	Internal oblique External oblique Transversus abdominis	Anterior abdominal wall	Inferior abdominal wall Upper lateral quadrant of buttock
Ilioinguinal	L1	Internal oblique	Anterior abdominal wall	Inferior medial inguinal ligament Genitalia
Genitofemoral	L1–L2	Cremaster	Testicular	Inferior medial inguinal ligament Spermatic cord
Lateral femoral cutaneous	L2–L3			Anterior, lateral and posterior aspect of the thigh
Femoral nerve				
1. Anterior division	L2–L4	Sartorius Pectineus	Medical aspect of the lower thigh Adduction of thigh	Anterior medial skin of the thigh
2. Posterior division		Quadriceps	Knee extension Patellar movement	Anterior thigh, hip, and knee
Obturator nerve				
1. Anterior division	L2–L4	Gracilus Adductor longus Adductor brevis Pectineus	Thigh adduction	Posterior medial thigh Medical knee Hip
2. Posterior division		Adductor magnus Obturator externus	Thigh adduction with lateral hip rotation	Knee

The nerves of the lumbar plexus provide sensory and motor innervation primarily to the anterior compartment of the thigh. Two of these nerves (genitofemoral and lateral cutaneous femoral nerve) pierce the psoas muscle and are at greater risk during lateral approach minimally invasive spine surgery. Table 2.4 contains detailed information on the nerves of the lumbar plexus.

The Sacral Plexus and Sciatic Nerve

The sacral plexus provides sensory and motor innervation to the posterior thigh, leg, foot, and pelvic area (Fig. 2.47). The sacral plexus is formed by the lumbosacral trunk as well as anterior divisions of S1–S3. The largest nerve of the sacral plexus is the sciatic nerve, having contributions from L4–S3. The sciatic branches form the tibial nerve and the common fibular nerve also called the peroneal nerve. Table 2.5 contains detailed information on the nerves of the sacral plexus.

Pudendal Nerve

The pudendal nerve receives a contribution from S2–S4 and innervates the genitalia as well as the sphincter muscles of the bladder, rectum, and anus. Pudendal nerve EMG monitoring using electrodes placed in the external anal sphincter is indicated when the lower sacral spinal cord segments are at risk (as is the case during surgery near the level of the conus medullaris) or when there is a significant risk posed to the cauda equina such as during a spinal cord untethering.

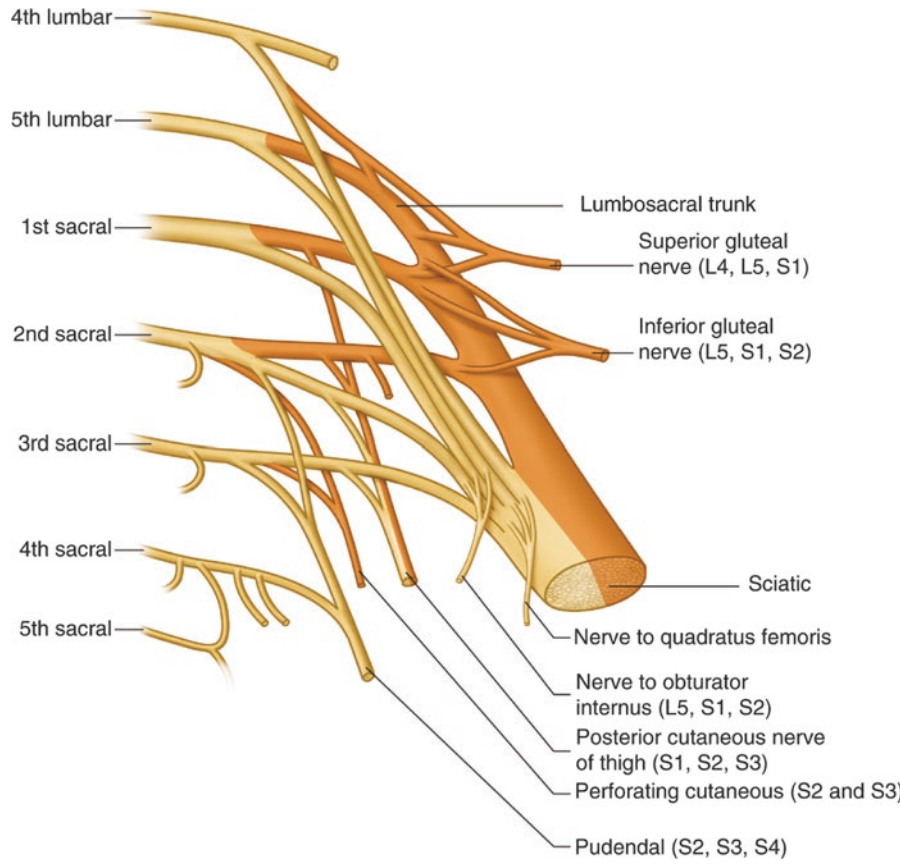


Fig. 2.47 Sacral plexus

Table 2.5 Nerves of the sacral plexus

Nerves	Segment	Muscles	Motion	Sensation
Sciatic nerve				
1. Tibial	L4–L5	Biceps femoris Semitendinosus Adductor magnus Popliteus Gastrocnemius Soleus Flexors of foot	Knee extension Plantar flexion Toe flexion	Heel Sole of foot Hip Knee Ankle
2. Superficial peroneal and deep peroneal	L4–S3	Biceps femoris Peroneus longus Peroneus brevis Extensors of foot Extensors of toes	Knee flexion Foot flexion	Anterior leg Dorsum of foot Knee Ankle
Deep		Extensors of foot Extensors of toes	Dorsiflexion of foot and ankle	Web space of the first toe Ankle
3. Sural	Components from peroneal and tibial	N/A	N/A	Posterior calf Lateral border of foot and fifth toe

Review Questions

1. Draw a diagram of the DCML pathway and discuss key synapses and structures within the pathway. Keep this diagram for study during the chapter on SSEP monitoring
2. Draw a diagram of the corticospinal tract and discuss key synapses and structures within the pathway. Keep this diagram for study during the chapter on MEP monitoring.
3. Draw a diagram of the neurovasculature and discuss key blood vessels and the territory that they supply. Keep this diagram for study of the effect of stroke on the varying electrophysiological signals you will be collecting and the resulting clinical manifestations in the patient.

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Cellular Neurophysiology

3

Scott Francis Davis

Introduction

The functional cell type of the nervous system is the neuron. Neurons are cells whose function is to process and transmit information through specialized connections called synapses. Neurons are electrically excitable cells, which means they are capable of transmitting an electric current known as an action potential. Neurons communicate with each other and with muscle cells by means of action potentials. This chapter will introduce you to basic neuronal morphology as well as the electrochemical basis of neurotransmission.

Neuronal Morphology

There are many types of neurons, but the many types can be boiled down to sensory neurons, motor neurons, or interneurons. Sensory neurons transduce external stimuli (such as touch, pain, temperature, light, sound) into action potentials that are moved throughout the nervous system to convey information. Motor neurons govern both voluntary and involuntary movement, generally in response to external stimuli. The role of interneurons is to relay information between neurons within the central nervous system.

A typical neuron has a cell body, or soma, that contains the nucleus and organelles. Two types of processes are found on a neuron. Dendrites are small processes emanating from the soma that receive incoming signals from other neurons. The axon proceeds from the cell body and functions to transmit impulses from the neuron onto other neurons or muscle cells. The axon hillock is the initial segment of the axon, rich in sodium channels, where the action potential is generated. The axon may branch along the way, and each branch ends as a specialized structure known as the terminal bouton. The terminal bouton lies adjacent to a postsynaptic element (the membrane of another neuron or muscle cell). Neuronal axons may contain an insulating material known as myelin at regular intervals along its length. Myelin is a lipid that is produced by support cells of the nervous system known as neuroglia. There are several types of neuroglia in addition to the ones that produce myelin. Schwann cells are the myelin-producing cells of the peripheral nervous system, and oligodendrocytes are the myelin-producing cells of the central nervous system. The spaces along the axon between myelinated segments are known as nodes of Ranvier. The purpose of this myelin sheath is to speed up conduction. Since myelin is an electrical insulator, action potentials will not cross myelinated segments of the axon

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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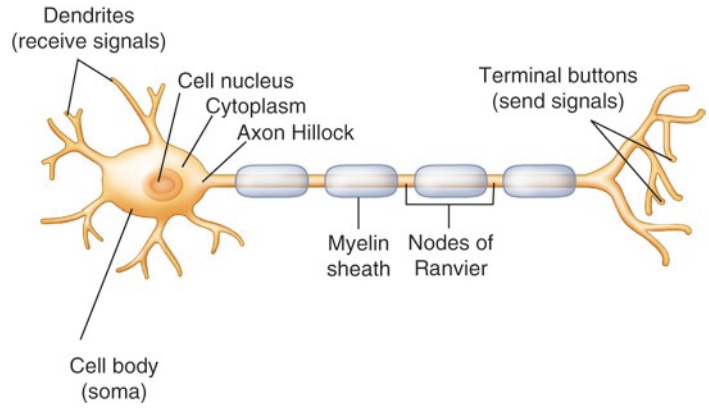

Fig. 3.1 The neuron

and instead jump between nodes of Ranvier. This type of conduction is known as saltatory conduction. Imagine if you were to skip between two points rather than walking step by step. You should arrive at your destination more quickly, albeit possibly a bit embarrassed. Figure 3.1 shows a typical neuron.

Neuronal Membrane

Like all mammalian cell membranes, the neuronal membrane is constructed of a phospholipid bilayer conferring upon the membrane the property of selective permeability (Fig. 3.2). Ions, charged atomic particles, are by nature hydrophilic and thus unable to freely cross the phospholipid cell membrane. This sets up a gradient across the neuronal membrane resulting in a separation of ions according to concentration and electrical charge. This is called an electrochemical gradient. Separation of ions is synonymous with separation of charge and is the basis of the neuronal membrane potential. Neurons and muscle cells are able to move charge (ions) across the membrane and are thus termed electrically excitable cells. This movement of ions is accomplished through transmembrane proteins that serve as ion channels. We will discuss the role of ion channels in maintaining the resting membrane potential as well as the generation of the action potential. For the sake of clarity, you should understand that the term "potential" refers to voltage, which is a measurement of the

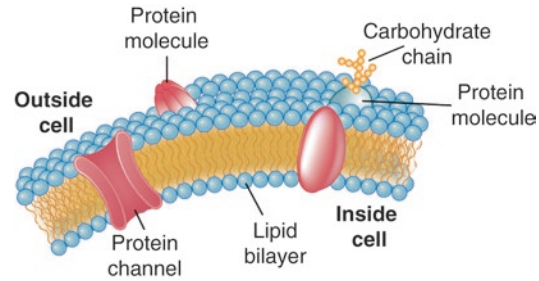

Fig. 3.2 Phospholipid bilayer. The neuronal cell membrane is composed of a phospholipid bilayer studded with transmembrane protein molecules. Among the varied functions of the transmembrane proteins is transporting ions across the cell membrane, an activity necessary for electrical excitability

force at which electricity (in this case ions) want to move down their gradient or toward the opposite charge.

Ion Channels

Ion channels are transmembrane proteins which provide a hydrophilic pore through which ions may pass between the cytoplasmic and extracellular sides of the membrane. Ion channels may be selective for either cations or anions or even for a specific ion. Ion channels are opened and closed in response to some event such as a change in membrane potential or the binding of a neurotransmitter.

Voltage-gated ion channels open and close in response to changes in the membrane potential

and are termed voltage-gated ion channels. These ion channels are involved in the propagation of the action potential. Each voltage-gated ion channel has a different activation range, defined as the range of voltages at which the channel remains open. The change in membrane potential that accompanies the opening of voltage-gated ion channels ironically results in their closure and the opening of other voltage-gated channels. Such an interplay occurs between voltage-gated sodium and potassium channels during the propagation of the action potential.

Ion channels that are gated by the binding of a molecule (ligand) are termed ligand-gated ion channels. Neurotransmitter receptors are a type of ligand-gated ion channel. The binding of a neurotransmitter to its receptor is responsible for the initiation of the action potential or other postsynaptic signaling events. Signaling between neurons is accomplished through neurotransmitter receptors. When a neurotransmitter binds its receptor, it induces a conformational change (opening) in the receptor protein allowing the passage of ions across the membrane. The result is a change in membrane potential that can lead to an action potential. We will discuss this in more detail later.

Excitatory neurotransmitters such as glutamate or acetylcholine bind to and open nonselective cation channels that allow Na+, K+, or Ca2+ to move across the membrane. Inhibitory neurotransmitters such as GABA and glycine bind to and open chloride channels.

Glutamate is the main excitatory neurotransmitter of the central nervous system. Acetylcholine (ACh), while found in the brain, is also the excitatory neurotransmitter of the neuromuscular junction. GABA is an inhibitory neurotransmitter found mainly in the brain, while glycine is the main inhibitory neurotransmitter of the spinal cord.

The Membrane Potential

The separation of ions across the membrane results in a recordable (nonzero) membrane voltage (Fig. 3.3). This resting membrane potential is approximately 60–70 mV in a typical neuron. By convention, we indicate the polarity of the potential with respect to the charge on the inside of the cell. The intracellular space bears a negative charge with respect to the extracellular space; therefore, we say that the usual resting membrane potential of a neuron is approximately −70 mV.

The term "potential" in membrane potential indicates that there exists the drive for ions to move across the membrane. Remember that these

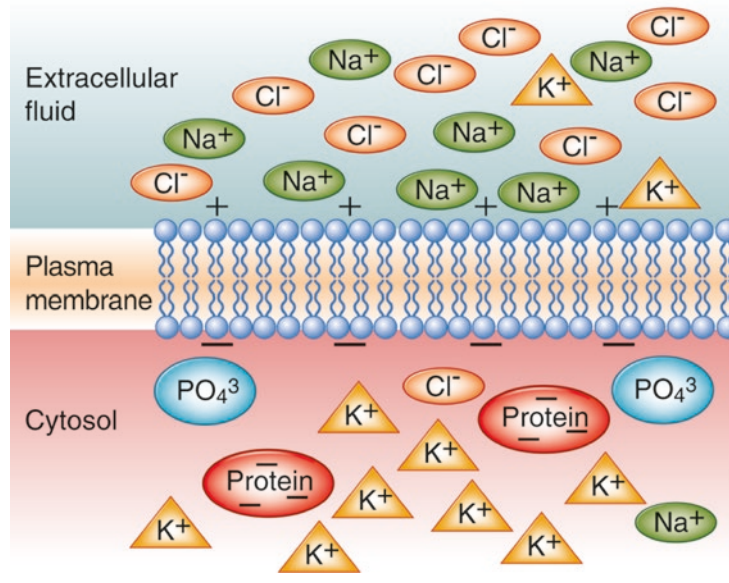

Fig. 3.3 Membrane potential. The separation of ions across the neuronal membrane is the basis of the membrane potential. Sodium is more abundant extracellularly and potassium is in greater concentration on the inside of the cell. Potassium leak channels and the sodium–potassium pump create a local negative charge along the intracellular membrane

ions are separated by the selectively permeable membrane and are unable to move freely. Ions want to move down their electrochemical gradient. If we were to allow ions to move freely across the membrane, the membrane potential would reach a value at which the ion was at equilibrium and there would be no net movement across the membrane. In other words, we would say the ion would be "happy." The membrane potential at which this would occur is called the equilibrium potential (also known as it's Nernst potential), and each ion has its own equilibrium potential. The potassium equilibrium potential is approximately −85 mV, while the sodium equilibrium potential is nearly +35 mV. Remember that the typical resting membrane potential is −70 mV. This means that potassium is much "happier" than sodium at rest; however, if allowed to move, it would still try and change the membrane potential to −85 mV.

The resting membrane potential is established and maintained by two mechanisms: potassium leakage out of the cell and the sodium–potassium pump (Fig. 3.4).

There are potassium channels which allow passive movement of potassium out of the cell (along its concentration gradient). This movement of positive charge out of the cell makes the membrane potential more negative (it is trying to reach −85 mV). These channels are called potassium leak channels. The potassium leak channels are the reason that the resting membrane potential lies so close to the potassium equilibrium potential.

So, if potassium is allowed to leak out of the cell, why does not the membrane potential reach the potassium equilibrium potential of −85 mV? The answer is the sodium–potassium pump. The sodium–potassium pump is a transmembrane protein; actually, it is an enzyme that hydrolyzes a molecule called adenosine triphosphate (ATP). Think of ATP as the energy source of the cell. The reason that the sodium–potassium pump hydrolyzes ATP is that it needs energy input to

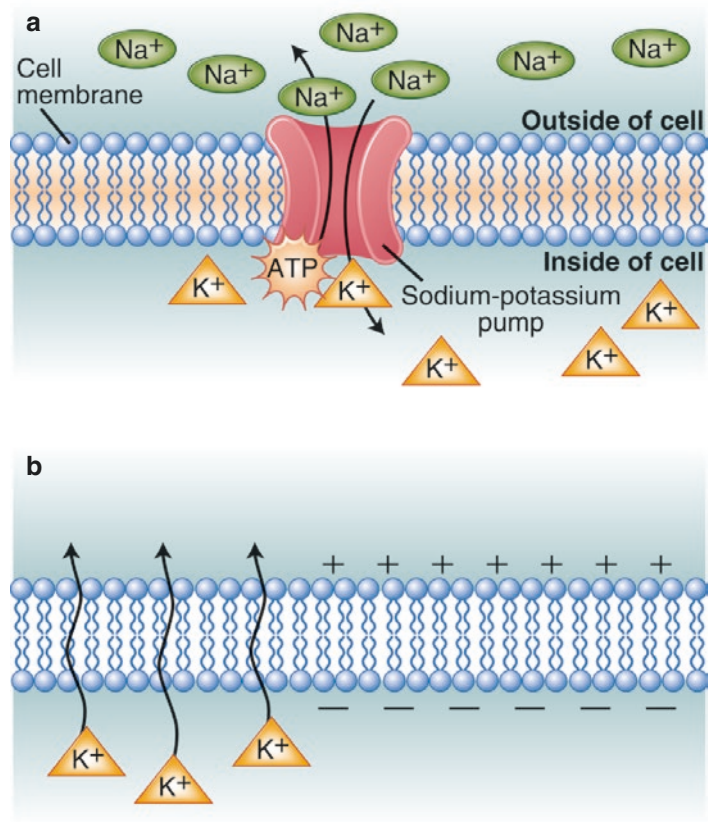

Fig. 3.4 (**a**) The sodium–potassium pump uses the energy derived from ATP to pump sodium and potassium against their concentration gradient. The pump moves 3-Na + ions out for every 2-K+ ions into the cell causing a net negative charge to form on the intracellular membrane. (**b**) Potassium leak channels contribute to the negative resting membrane potential, and this leak must be balanced by the sodium–potassium pump so that the resting membrane potential does not run down leaving the cell unexcitable

perform its function. The role of this pump is to move three sodium ions from the intracellular to the extracellular space and two potassium ions from the extracellular to the intracellular space. This is *against* the concentration gradient of both of these neurons, hence the reason we needed energy input. The sodium–potassium pump is said to be electrogenic because it moves three positive charges out of the cell for every two positive charges into the cell. This creates a net charge of −1 inside the cell.

The Synapse

Signaling between neurons is through electrochemical transmission across the synapse. The synapse is the point of communication between neurons or between a neuron and muscle (Fig. 3.5). The synapse consists of a presynaptic membrane (the terminal bouton) and a postsynaptic membrane (a dendrite or muscle end plate). A small space, the synaptic cleft, separates the pre- and postsynaptic membranes. When an action potential is propagated down the axon of the presynaptic neuron, it invades the terminal bouton and opens voltage-gated calcium channels allowing calcium into the terminal. This sets up a chain of events resulting in the release of a neurotransmitter into the synaptic cleft. Neurotransmitter in the cleft binds to its specific receptor on the postsynaptic membrane allowing ions to move across the membrane. If the neurotransmitter is excitatory (e.g., glutamate), sodium and potassium move into the postsynaptic neuron and the membrane potential moves in the positive direction. If an inhibitory neurotransmitter is released, chloride is the ion that moves and the membrane potential becomes more negative.

Postsynaptic Potentials

The movement of ions across the postsynaptic membrane in response to neurotransmitter binding creates a measurable change in the membrane potential of the postsynaptic cell. Excitatory signals cause a depolarization of the cell, while inhibitory signals result in hyperpolarization (the membrane potential becomes more negative). At any moment, a neuron is receiving multiple synaptic inputs (up to millions), some of them excitatory and some inhibitory. Each input generates a change in the membrane potential called a postsynap-

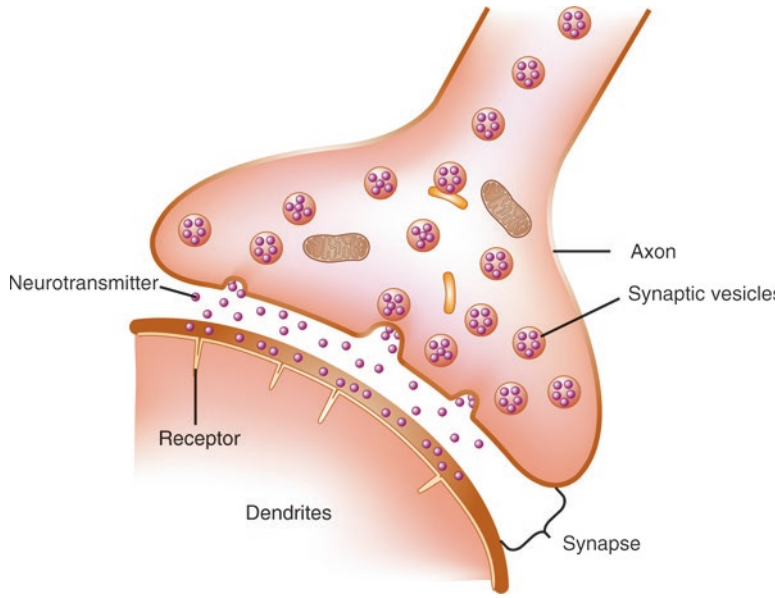

Fig. 3.5 The synapse

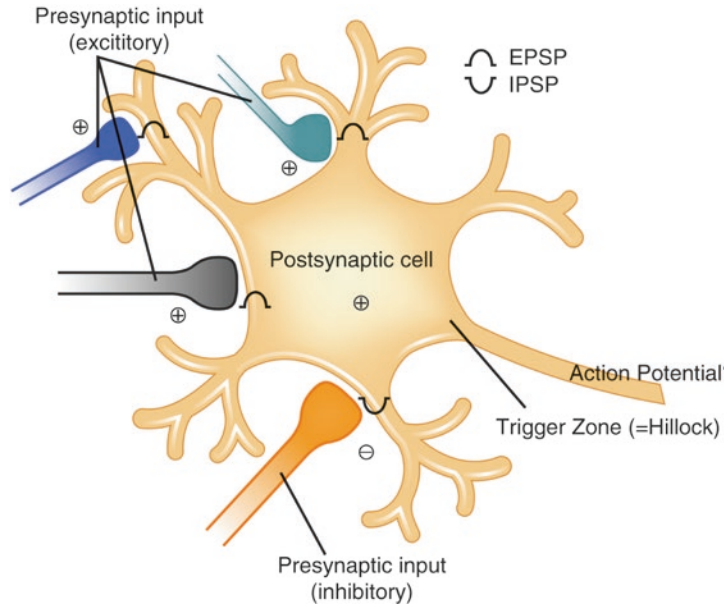

Fig. 3.6 Postsynaptic potentials. An example of a neuron receiving both EPSPs and IPSPs that will summate to possibly generate an action potential

tic potential (PSP). A PSP may be excitatory (EPSP) or inhibitory (IPSP). EPSPs depolarize the neuron, while IPSPs hyperpolarize the neuron. PSPs decay with distance traveled across the membrane in contrast to action potentials which continually renew and self-propagate (Fig. 3.6).

Summation

PSPs summate and the effect on the membrane potential is equal to the summated PSPs. For example, if an equal number of EPSPs and IPSPs of equal magnitude reach the postsynaptic membrane at the exact same time, they cancel each other out, and there is no change in postsynaptic membrane potential. A greater number or magnitude of EPSPs depolarize the cell, while a greater effect of IPSPs will hyperpolarize the membrane. Summation of PSPs can be either temporal or spatial (Fig. 3.7). Temporal summation occurs from the overlap of PSPs that occurs when synaptic input is occurring at a high frequency. Spatial summation occurs in response to multiple convergent inputs to the cell at the same time. The concept of summation is important when you move on in Chap. 7 to study the way the corticospinal pathway directs voluntary movement and how the monitorist has to replicate this physiological phenomenon when monitoring motor evoked potentials.

Action Potentials

Action potentials are the short-lasting electrical events that drive communication between neurons and between neurons and muscle cells. Action potentials occurring in muscle cells are the first step in a chain of events leading to muscle contraction. Unlike PSPs, action potentials are "all or none," meaning they do not vary in amplitude. They also self-propagate all the way down the axon as opposed to PSPs which decay with distance. In order for a neuron to fire an action potential, the neuronal membrane must depolarize to a specific voltage called the threshold. The membrane may reach threshold in response to the summation of EPSPs received as the signals of presynaptic neurons. A predominance of IPSPs will bring the membrane potential further from threshold and prevent the cell from firing an action potential.

When EPSPs summate allowing the neuron to reach threshold, voltage-gated sodium channels open allowing sodium into the cell and causing a

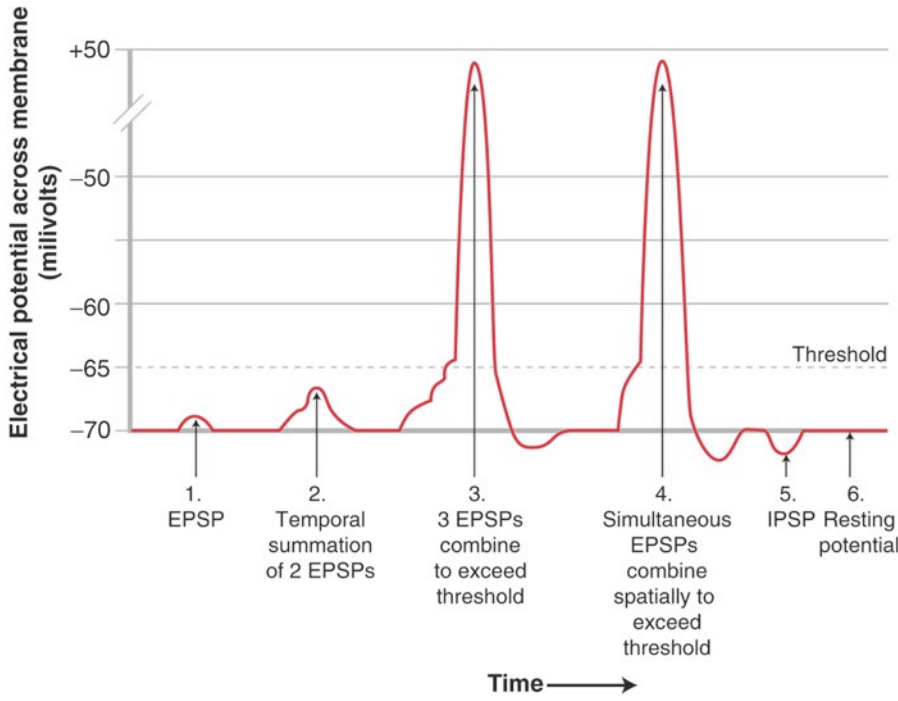

Fig. 3.7 Summation of postsynaptic potentials

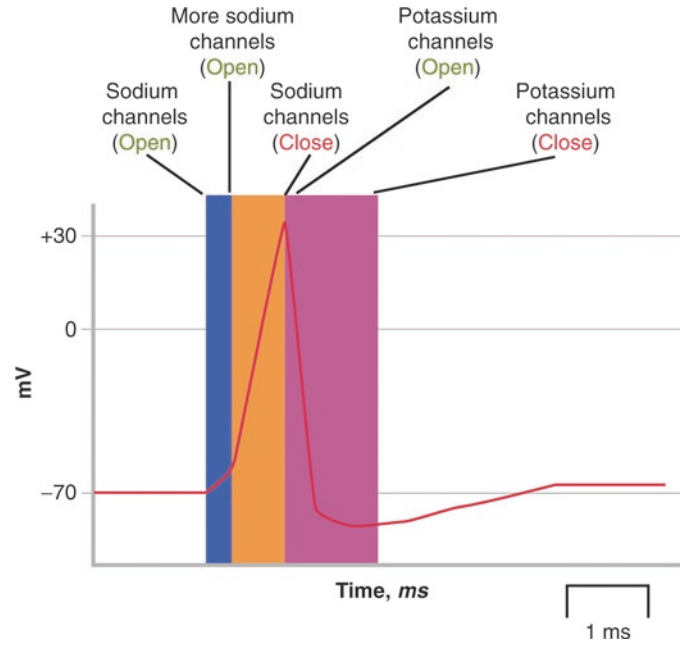

Fig. 3.8 The action potential. The interplay between voltage-gated sodium and potassium channels contributes to action potential generation

further depolarization. The influx of sodium will cause the membrane potential to move toward the sodium equilibrium potential (around +35). Before the membrane can reach the sodium equilibrium potential, the voltage-gated sodium channels will close (as the membrane potential moves outside of their activation range) and voltage-gated potassium channels will open ushering potassium into the cell and returning the membrane potential to rest (Fig. 3.8).

The depolarization of the membrane during an action potential is so strong that adjacent segments of membrane become similarly depolarized causing the action potential to propagate down the axon. This self-propagation ensures that action potentials travel the entire length of the axon without decrement.

Neuromuscular Junction and the Motor Unit

The synapse between a neuron and muscle fiber is a specialized structure known as the neuromuscular junction. The presynaptic neuronal membrane lies adjacent to the end plate which is a specialized area of the sarcolemma, or muscle cell membrane.

Acetylcholine (ACh) is the neurotransmitter released by the neuron into the synaptic cleft, and ACh will bind its receptors on the muscle end plate. ACh receptors are nonselective cation channels that depolarize the muscle. This depolarization is the first step in a chain of calcium-dependent events leading to contraction of the muscle fiber.

Muscle fibers may receive input from only one axon terminal; however, each axon terminal may contact one or multiple (thousands of) muscle fibers. The axon terminal and all of the muscle fibers it innervates are called the motor unit (Fig. 3.9). Motor units may be small with axon terminals synapsing with very few muscle fibers or they may be large with each axon innervating thousands of muscle fibers. Muscles that require fine motor control are part of smaller motor units, while power muscles (such as those in the legs) are part of larger motor units.

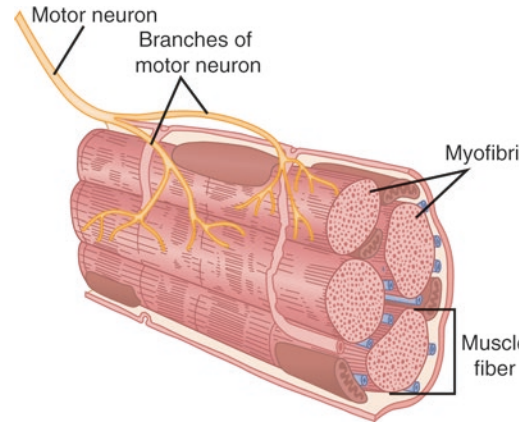

Fig. 3.9 The motor unit

Review Questions

1. What is the difference between temporal and spatial summation? Draw a diagram illustrating these two types of summation.
2. Why would some muscles be part of smaller motor units while others are part of larger motor units? Remember from Chap. 1 that structure subserves function.
3. How is the sodium–potassium pump responsible for establishing the resting membrane potential?

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4 Electrophysiology and Bioinstrumentation

Scott Francis Davis and Jeremy Andrew Bamford

Introduction

Fundamental to intraoperative monitoring are the principles of electrical recording and stimulation of neural tissue. The monitoring clinician in the surgical suite will record neural activity that is both spontaneous and evoked by electrical stimulation in order to monitor and map the nervous system and ensure intact neural pathways. A conceptual understanding of these processes is one of the main pillars upon which the field of intraoperative monitoring is based. In the early history of intraoperative monitoring, neurophysiologists conceived of and built their own systems for electrically interfacing with the patient's nervous system. Today, the equipment is purchased from companies that manufacture advanced monitoring devices. These devices automate many of the calculations that had to be performed manually in the past. Nevertheless, the monitoring clinician in the surgical suite must have a working understanding of bioinstrumentation and electrical stimulation and recording techniques in order to ensure valid testing of neural function.

Ohm's Law: The Basis of Bioelectrical Stimulation and Recording

There is a predictable relationship between current, resistance, and voltage. The flow of current across a resistive medium such as biological tissue generates a potential (also known as voltage or electromotive force). This relationship can be expressed mathematically as $V = IR$ and is known as Ohm's law. We can see that the potential (or voltage, V) generated is the product of the current applied (I) and the resistance (R) of the circuit to that current. Current is measured in amperes (A). It is worth noting that current is not a measure of the total charge delivered but actually the rate at which charge is delivered. The movement of charge is expressed in coulombs (unit of charge) per second. We can say that 1 A = 1 c/s. Although stimulus intensity is often given in milliamperes, the more clinically relevant issue is often the total charge delivered over a given procedure or even the total charge per stimulation phase (i.e., mono- or biphasic stimulation). Note that voltage can also be abbreviated (E) as in electromotive force. You may see this convention on the CNIM exam.

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

J. A. Bamford
Department of Anesthesiology, Louisiana State, University Health Sciences Center, New Orleans, LA, USA

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Stimulation

Both nervous and muscular tissues are electrically excitable (sometimes referred to as irritable), meaning that they can be excited to activation with the application of an electrical current across their membranes. Electrical excitability is derived from the presence of voltage-gated ion channels embedded in the membrane (see Chap. 3 for a review of ion channels). Applying an electrical field across these tissues causes a depolarizing voltage potential across the membrane. If this depolarization is sufficient, the threshold for activation of the voltage-gated channels will be reached causing them to open and allow ions to flow along their gradients and generate an action potential. This action potential is primarily a function of sodium ions flowing into the cell from the extracellular space. If generated along an axon, the resulting action potential will propagate in both directions away from the original site of depolarization. From this point on, the electrically generated action potential is indistinguishable from physiologically generated signals. Electrical stimulation of the nervous tissue may be used to monitor the functional integrity of the nervous system during surgery. For the purposes of intraoperative monitoring (IOM), we generally use gross stimulation of peripheral nerves, nerve roots, and the cerebral cortex rather than discrete stimulation of individual neurons. The result of this method of stimulation is recruitment of many (thousands or more) individual axons or cortical neurons.

Stimulating Electrodes

Stimulating electrodes have two poles: the cathode and the anode. The cathode is the stimulating pole and is the source of the current. The anode is called the return or current sink. Current will flow from the source generator to the cathode and return to the source generator via the anode. Note that it is inaccurate to refer to the anode as the ground. Although you will hear people do so, the ground is a different electrode and not part of the stimulating electrode.

To achieve controlled stimulation and pass an electrical current across the tissue, a cathode and anode must be in place. The stimulating electrodes can be arranged in a monopolar or bipolar configuration. In the monopolar variant, the cathode and anode electrodes are placed at some distance from one another. Usually, the cathode is placed nearer the tissue to be stimulated while the anode is placed at a distant site, often near a bony prominence or other location away from excitable tissues. This configuration generates a more diffuse electrical field that is appropriate for some stimulation tasks such as checking implanted screws for a pedicle wall breach or searching for a nerve within the surgical field. This configuration also offers a great deal of sensitivity with little specificity. This means that the recorded waveform will be sensitive to electrical recordings over a larger anatomical area, but the monitorist will not have specific information on which structure is generating the waveform. When it is desirable to achieve a higher degree of specificity while stimulating, such as for cranial nerve or cortical stimulation, a bipolar electrode configuration is used. A bipolar configuration involves placing the cathode and anode closer together, often directly apposed across a specific nerve. Bipolar configurations limit the spread of current, generate greater selectivity of the excited neural tissues, and typically produce lower nerve activation thresholds. Common bipolar stimulation tasks include somatosensory evoked potentials where a distal nerve is activated to evoke a cortically measured response. In these tasks, the cathode must be placed in a proximal position relative to the anode to avoid a condition known as anodal blocking. Anodal blocking occurs when a positive charge builds up under the anode. The nerve underlying this area of positive charge may become hyperpolarized leading to the abolition of any action potential attempting to travel through this region. For this reason, the cathode is always placed proximal to the anode when attempting to electrically excite a nerve (for SSEPs) with a bipolar configuration. Anodal block is a commonly tested concept in the CNIM exam.

Commercially available handheld monopolar and bipolar probes are available for a wide

range of uses. Direct stimulation of peripheral nerves for the purposes of recording a nerve action potential close to the stimulation site is actually best achieved with a tripolar stimulator. Tripolar stimulators have a cathode flanked on either side by anodes. This reduces the recorded stimulation artifact and provides a very discrete stimulation site.

Stimulus Pulse

When stimulating electrically excitable tissues, we commonly make use of square-wave pulses of monophasic or biphasic configuration (Fig. 4.1). Square-wave pulses are rapidly rising pulses with simple morphologies that can be described by their pulse duration (or width) and pulse amplitude, usually referred to as stimulus intensity. Monophasic square pulses are of simpler configuration and are suitable for most stimulation tasks in the periphery where the cumulative length of stimulation is likely to be short. An example of this would be pedicle screw testing where the cumulative length of stimulation during a procedure can be measured in seconds. Biphasic pulses are more complex but have the advantage of being charge-balanced. This results in no net charge being deposited at the electrode–tissue interface. For stimulation tasks requiring prolonged stimulation times, a biphasic pulse should be selected in order to avoid corrosion of the electrode and deposition of potentially toxic substrates at the electrode–tissue interface. This is especially important when directly stimulating the cortical surface. Chronically implantable stimulators such as deep-brain stimulators or epidural stimulators commonly employ biphasic, charge-balanced stimulation. Electrodes used for these stimulation tasks are frequently made from noble metals such as platinum or iridium rather than stainless steel. A combination of these metals is necessary to avoid corrosion or pitting of the electrode in a system that is designed to remain chronically active over years of use. Most stimulation tasks performed during a typical procedure will employ monophasic pulses. The most common exception is repetitive high-frequency continuous stimulation for brain mapping as may be performed by a device such as the Ojemann stimulator.

Chronaxie and Rheobase

Rapidly rising, square-wave pulses of either mono- or biphasic configuration can be described by their pulse duration and pulse amplitude. In order to understand the contributions of pulse duration and amplitude on the selectivity of neural stimulation, Lapicque undertook a series of investigations in the early

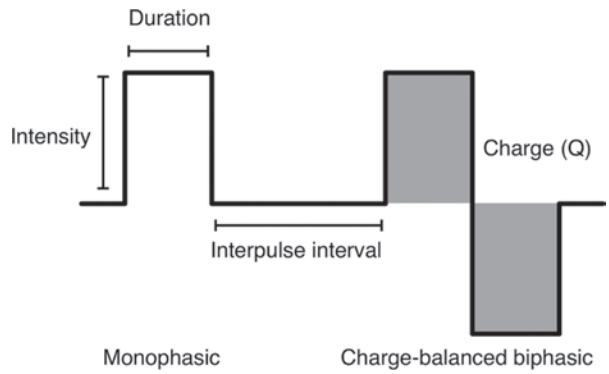

Fig. 4.1 Electrical stimulation is accomplished with simple square pulses, either monophasic or biphasic in nature. The pulses are described by their intensity (current) and pulse duration (time). The total charge is the product of current and time. Symmetrical, biphasic pulses can be described as charge-balanced indicating that no net charge is delivered to the target tissue. The frequency of stimulation in Hz is the inverse of the interpulse interval

1900s using constant-current pulses. Lapicque described two concepts that illustrate the interaction between pulse duration and pulse amplitude and the excitability of neural tissues (Fig. 4.2). The first of these is rheobase, which is the minimum stimulus amplitude needed to excite the target tissue given an infinitely long pulse duration (practically speaking, >10 ms). Lapicque further discovered that doubling of the pulse amplitude from its rheobasic intensity greatly diminished the stimulus pulse duration necessary to excite a given tissue, thus reducing the total energy necessary to achieve excitation. The pulse duration at twice the rheobasic strength, he coined as chronaxie. It has been shown that chronaxie may vary across neural tissues. While most white matter tracts have chronaxie values in the 50–100 μs range, gray matter structures can have chronaxie values above 200–700 μs. As a practical matter, while stimulating in the periphery, a pulse duration of 100–300 μs is often chosen as the selectivity of neural structures is less important for these tasks. One exception to this is the recruitment of H-reflexes where a pulse duration of 1000 μs is typically selected in an attempt to preferentially recruit sensory fibers (see Chap. 12 on H-reflexes). When directly stimulating the cortex, the pulse duration is typically kept shorter (50–100 μs) in an attempt to avoid exciting cell bodies, which may lead to ictal activity.

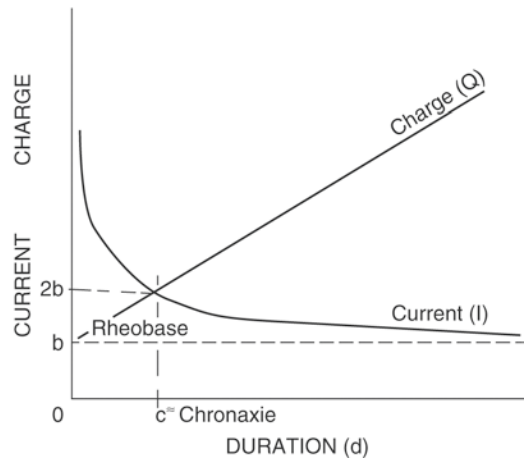

Fig. 4.2 Rheobase is the minimum stimulus amplitude needed to excite the target tissue, given an infinitely long pulse duration. Chronaxie is the pulse duration that excites neural tissue at twice the stimulus intensity of rheobase. This point also represents the lowest charge (Q, the product of stimulus intensity and pulse duration) at which the tissue can be excited

Constant Current Versus Constant Voltage

Electrical stimulation can be applied in either a constant-current (current-regulated) or constant-voltage (voltage-regulated) manner. In the case of regulated voltage, the electromotive force (V) is held constant while the current (I) is allowed to fluctuate in response to changes in resistance (R), as dictated by Ohm's law. As a result of this method of stimulation, the charge and electrical field will fluctuate as current varies in response to changing resistance. Fluctuating resistance will result from changing conditions at the electrode–tissue interface; for example, if an electrode is slightly repositioned or the composition of the conductive medium that surrounds the electrode is altered. As the charge and electrical fields vary between stimulus trials, the elicited response may become unstable. Voltage-regulated stimulation is susceptible to unstable responses due to this alteration of charge and electrical field. In the case of current-regulated stimulation, the current is held constant while the voltage is allowed to fluctuate in response to changing resistance. The primary advantage of this configuration is that the charge and electrical field generated are more consistent, resulting in a more stable response. This makes current-regulated stimulation preferable for environments prone to rapid and extreme changes in resistance such as an open craniotomy.

Concluding Thoughts on Stimulation

It is important for the monitoring clinician to be able to understand the variable methods of electrical stimulation in order to appropriately apply current in a safe and effective manner. An understanding of the concepts discussed

will give the monitoring clinician the tools to be ableto reason through a stimulation task and select the appropriate stimulus parameters. We can, however, sum up with some general recommendations for common stimulation tasks. Most of the stimulation tasks in the surgical suite will utilize bipolar stimulation (most evoked potentials, somatosensory evoked potentials, direct nerve stimulation), with the most obvious exception being pedicle screw stimulation. Likewise, most of the pulses will be monophasic in configuration, with the most obvious exception being direct cortical stimulation for brain mapping. Pulse duration will be in the range of 100–300 μs except for H-reflexes (1000 μs) and cortical mapping (<100 μs). Most tasks will employ a constant-current stimulation (pedicle screw stimulation, direct nerve stimulation, somatosensory evoked potentials, direct cortical stimulation using the Ojemann system), while others will employ constant-voltage stimulation (motor evoked potentials). For more specific recommendations, the reader is referred to the chapters contained within this volume for each modality.

Recording

Recordings of electrical responses can be made from tissues that generate or transmit electrical signals. This process generates differences in electrical potential between anatomic structures, which can be recorded by electrodes. Potential differences are generated by structures such as muscles, axons, and synapses that propagate electrical signals by the movement of ions across a membrane. Although a great many signals can be gleaned during an operation, those that relate to the integrity of underlying structures that might be injured during the procedure are identified for intraoperative monitoring. The presumption of intraoperative monitoring is that significant changes in the recorded signals represent potential injuries while preservation of baseline values should ensure that these structures and their associated functions are unaffected.

Recording Montages

Recording nomenclature can easily be confused with stimulation nomenclature. Most commonly, we make use of three montages or recording configurations. A referential recording is made whenever one electrode is placed over or near a generator of interest while a distant reference is placed in an electrically indifferent location such as over a bony prominence where little signal is expected. For instance, an electromyography (EMG) recording can be made from the medial gastrocnemius muscle with one electrode inserted over the belly of the muscle and a distant reference inserted over the medial malleolus. Such a configuration would have the advantage of sharing a large proportion of the ubiquitous electrical noise in common between the two channels, while not sharing much of the true signal of interest generated from the muscle. Referential montages are thought to give the largest signals; for this reason, they share little true signal in common between the two inputs, yielding little rejection of the true signal in the differential amplifier. A bipolar recording montage, not to be confused with bipolar stimulation, would be made if the distant electrode from the referential example mentioned earlier was moved from the medial malleolus to the medial gastrocnemius muscle. A bipolar recording is made when both recording electrodes are much closer together resulting in both electrodes recording some of the signal of interest. While less sensitive to activity generated at distances further from the electrodes, this configuration is highly specific. For this reason, bipolar recording is the most common montage employed in intraoperative EMG. The two adjacently placed inputs are ideally suited for recording the medial gastrocnemius muscle activity, although we can expect recordings of lower amplitude as some of their signals will be common to both inputs and thus be rejected by the differential amplifier. In practice, EMG signals are generally so large that a reduction of signal amplitude will be an acceptable trade-off when considered against the specificity advantage derived from the bipolar montage. Finally, we can also place needles in an active-referential

montage by moving one of our needles to the lateral gastrocnemius muscle. By doing so, we tie the medial and lateral gastrocnemius recordings together. The advantage of this configuration is that we can cover a larger number of muscles with fewer channels. When using modern intraoperative monitoring systems, this is often unnecessary as these newer machines have an ample number of channels (often 16–32) and there is no need to conserve channels for most procedures. The most likely exception would be a complex scoliosis procedure covering large areas of the spine and requiring monitoring from many muscles simultaneously. Should active-referential montages become necessary, the monitoring clinician must remember to combine muscles that arise from the same nerve root levels. For instance, creating a channel with one input over medial gastrocnemius, arising from the L5–S1 nerve roots, and another over tibialis anterior, arising from L4–L5 nerve roots, would be inappropriate as the monitoring clinician would be unable to accurately inform the surgical staff of the nerve root level at risk if EMG firing was noted from this channel. Similarly, a channel derived from a combination of biceps (C5–C6 nerve roots) and triceps (C6–C7) nerve roots would be inappropriate.

Volume Conduction

Volume conduction is the movement of charge through a conducting medium such as an ionic solution like salt water. This charge does not propagate in a directed manner; rather it radiates in all directions. As such, it follows the inverse-square law along with other radiant phenomena such as light and sound. The inverse-square law states that the intensity of a signal will decrease with the square of distance. This radiant behavior means that a recording of a volume-conducted signal will weaken with distance in any direction from the signal source. As currents move through the body, they interact with recording electrodes, producing a potential difference between the electrode pair and resulting in a signal that can be recorded and interpreted. For example, summated signals from neuronal populations generate electrical potentials recorded from scalp electrodes, with individual neurons having their own contribution to that population signal. If the individual neurons are arranged randomly, these potentials will cancel each other out, yielding no recordable signal. This is described as a closed electrical field and can be observed in the configuration of many brain nuclei. Fortunately, many of the signal generators of interest to neurosurgical procedures are arranged in an ordered manner, yielding an open electrical field and signals that can sum together and be recorded at a distance. For example, pyramidal neurons of the neocortex are arranged in layers and columns. These neurons fire synchronously, resulting in a large potential that is oriented across the recording electrode and thus, is recordable.

With most recordings made in the surgical suite, it is impractical to place the recording electrodes directly in contact with the signal generator. As such, recorded signals are almost always transmitted to the electrode via some degree of volume conduction.

Understanding Current Sources

Although the reality is more complex, sources of current in the body can be modeled reasonably well by imagining that the body is a homogenous container filled with a conductive saline solution. In this situation, a single current source will radiate current spherically with an intensity that declines with the square of distance. This is referred to as a monopole. Potentials around this perfect monopole will be equivalent at equivalent distance from the current source. Any potential measurement made at a given distance from the monopole will be equivalent so long as the radius from the source is kept constant. We can envision shells of equivalent potential strength, known as isopotential or equipotential field lines surrounding the monopole. However, true monopoles rarely exist. More commonly, current flows between two oppositely charged locations creating a dipole. A dipole consists of two oppositely charged areas, one a source and one a sink, with current flowing between them. Many of the corti-

cal generators measured in the surgical suite can be modeled as dipoles. Dipoles generate fields of opposing polarity across their midline. Relative to an indifferent reference, a potential measurement on one side of the midline will be equal in strength but reversed in polarity from one made on the other side. At the midline, the fields generated by the opposing poles of the dipole will cancel out, creating a plane of zero potential strength. This feature can be taken advantage of when mapping the cerebral cortex as the plane of reversal corresponding to the central sulcus (Fig. 4.3).

Near- and Far-Field Recordings

Recordings are often referred to as either near or far field. Although these terms describe distance relative to an electrical field generator, the concepts are only indirectly related to the distance between the recording electrode and the electrical generator of interest. There are significant underlying biophysical properties that distinguish how near- and far-field recordings must be made in electrically noisy environments like the surgical suite.

Near-field potentials are generally recorded by electrodes placed directly on the field generator or in close proximity. Although these recordings are made in close proximity to the generator, they are still compound recordings or the sum of multiple potentials. Near-field potentials tend to be specific to a discrete neural structure. Near-field recordings can be either bipolar (closely located reference) or referential (distant reference).

Far-field potentials are those recorded at a distance from the generator. As such, they tend to record the contributions of multiple structures and can be less easily identified with a specific structure. The amplitudes of far-field potentials tend to be lower than those of near-field potentials, and they usually require signal averaging of multiple sweeps in order to detect the signal from

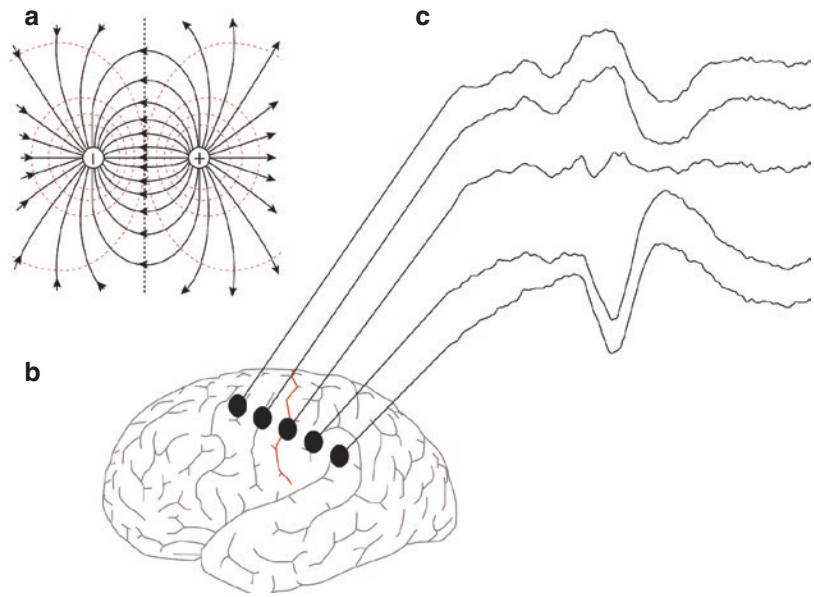

Fig. 4.3 An example of a perfect dipole (**a**), comprising a current source and sink, and the field lines between them. The intersecting midline plane is an area of zero potential strength. Many neocortical generators can be modeled as current dipoles. An example is shown in (**b**) as the central sulcus divides the sensory areas (postcentral gyrus) from the motor strip (precentral gyrus). A grid of sensors can be laid across this strip, and evoked potentials can be recorded in response to sensory nerve stimulation (**c**). The reversal of phase from an upward deflection to a downward deflection in the recording represents the intersecting midline of zero potential generated from this structure. This can be used by the neurophysiological team to aid the surgeon in demarcating motor and sensory areas

extraneous background noise. When recording far-field potentials, both electrodes are relatively distant from the generator source.

Noise

In any observation of a physical phenomenon, there is bound to be some error in the course of measurement. This is known as measurement error and is defined as the difference between the actual or true score and the observed score of a phenomenon. This is a real but intangible concept as the degree to which a measurement is contaminated with error can never be known perfectly. When making electrophysiological recordings, we often refer to measurement error simply as "noise." Ultimately, noise is any portion of the signal that may obscure the true signal. Sources of noise in the surgical suite can be varied, but one ubiquitous generator of noise emanates from electrical sources. In order to reduce the various noise components of our recorded signals, we employ many methods including isolation of recording equipment from sources of noise, differential amplification, filtering, and signal averaging. The ultimate goal of all of these efforts is to maximize the signal-to-noise ratio (SNR).

Signal-to-Noise Ratio

SNR is the expression of the amplitude of the signal as a ratio with the amplitude of the unwanted noise. Mathematically, the peak-to-peak signal is divided by the largest peak-to-peak noise sample in the recording to calculate SNR. By convention, signals with SNR >2:1 are accepted and considered reliable. Signals with SNR <2:1 are deemed unreliable and should be treated as unmonitorable until the SNR can be improved. Although the calculation of SNR is simple, the optimization of SNR involves a troubleshooting process that can be involved. The basis of the optimization of SNR is achieved with an understanding of the concepts of amplification and filtering that will be explained in the following sections.

Amplification

Neurophysiological signals range in peak-to-peak amplitude from <1 μV up to a few mV. In order to assess signals this small, it is necessary to increase the signal size, a process known as amplification. Ideally, amplification should increase the power of a signal without modifying its latency or morphology. The degree to which amplification increases signal power is called the gain. Gain can be expressed as the ratio of the amplitude of the output signal to the amplitude of the input signal (V_{out}/V_{in}). For instance, the gain might be set at 10:1 or 1000:1 signifying that the output signal is more powerful than the input by a factor of 10 or 1000, respectively. As the factor rises to amplify very small signals, it becomes convenient to express such large numbers using a logarithmic transform, the decibel scale. Decibels are calculated as 20 times the base-10 logarithm of the gain ratio ($20 \times \log 10\ (V_{out}/V_{in})$. The decibel scale is convenient because it can express a large range using small numbers and because the gain of amplifiers in series can be added together to determine the final gain, rather than multiplying the untransformed factors together.

It should be noted that the term "gain" is improperly used in many intraoperative systems. True gain is an amplifier property, not a display sensitivity setting. In most systems, both the gain (i.e., the ratio of signal amplification in the amplifier) and the display sensitivity (the setting that alters the way the signals are displayed onscreen) can be adjusted. However, the monitoring clinician must always understand that these are not the same thing. Both the gain and the display sensitivity must be optimized if neurophysiological signals are to be properly interpreted.

Differential Amplification

The first stage of amplification is accomplished by a preamplifier. Preamplifiers are designed to produce low-noise amplification to the order of $10 \times -1000 \times$ (20–60 dB). Preamplifiers are often placed close to the signal source to prevent contamination from sources of noise.

Preamplification is necessary in order to increase the signal strength and maintain SNR before the signal is contaminated by any noise or interference. Once the signal strength is boosted by 20–60 dB, a later introduction of noise is much less likely to alter or abolish the signal.

In clinical settings, secondary amplification makes use of differential amplifiers that allow us to alter the gain of the amplification in order to optimize the output signal. In addition, differential amplifiers increase the components of the signal that differ between two inputs. These two inputs are referred to as the inverting and noninverting inputs, or sometimes, as the active and referential inputs, respectively. Measurements are made from each input with reference to ground, the signal presented to the inverting pole of the differential amplifier is inverted, and the two inputs are added together (Fig. 4.4). The principle of differential amplification is that much of the signal that is common to both inputs is likely to be noise and should be eliminated in order to allow the true signal to be revealed. For instance, electrical noise at 60 Hz is a ubiquitous contaminant in the surgical suite and can be greatly reduced by this process as all inputs are likely to share a great deal of this noise in common. In contrast, true neurophysiological components of the signal are likely to vary as they are recorded by inputs placed at different locations.

Common Mode Rejection

The efficiency of rejection of common signals between the two inputs of the differential amplifier can be measured as the common mode rejection ratio (CMRR). The CMRR is often expressed using the same 20 log rule that is invoked for expressing the gain of an amplifier. The American Clinical Neurophysiological Society recommends that differential amplifiers used in the surgical suite have a CMRR of at least 80 dB or a 10,000:1 ratio of rejected to passed signals. In reality, modern equipment has a higher CMRR. It should be stressed that this process is dependent upon a low-impedance ground (<5 kΩ) and upon equal impedances between the two inputs (roughly equivalent to each other and also <5 kΩ) entering the differential amplifier. A high-impedance ground or significantly different impedances from the input

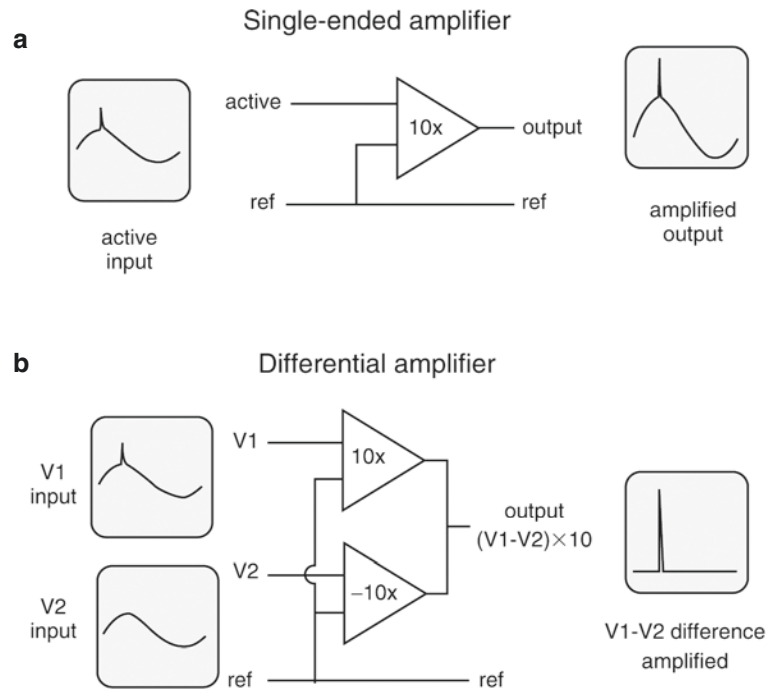

Fig. 4.4 In part (**a**), a single-ended amplifier is shown in which the input signal is simply increased in amplitude. No distinction is made between the active and referential inputs in this configuration. In (**b**), the differential amplifier compares the two channels, inverts one, and sums the final product together. Signals common to both inputs will be canceled, while differential signals will be amplified

electrodes often signify that the electrodes have been placed improperly and should be checked as this will result in a reduction of the CMRR and significant contamination of the true signal with noise.

Filters

Neurophysiological signals can be broken down into their component frequencies and visualized as a power spectrum with power on the ordinate (vertical axis) and frequency on the abscissa (horizontal axis) (Fig. 4.5). When this is done, we can see that neurophysiological signals collected in the surgical suite have frequency boundaries, beyond which no useful signal exists. Furthermore, there are frequencies that carry the bulk of the signal power and should be preserved if we are to accurately record a signal. The process of eliminating irrelevant frequency components and preserving critical ones is electronic filtering. A number of filter types exist, and their use can enhance or invalidate the recording process. Common filters include bandpass filters, notch filters, and artifact rejection filters. Furthermore, the filtering steps can be accomplished with analog or digital filters that produce a permanent or reversible modification of the incoming signal, respectively. Typically, all these filters are employed in their proper place to aid in the recording of neurophysiological signals and optimize SNR (Fig. 4.6).

Bandpass

Extraneous signal energy that exists beyond the reasonable frequency range of a desired neurophysiological signal can be eliminated with bandpass filters. The bandpass is created by the use of low- and high-frequency filters (LFF and HFF). Some will refer to these as high-pass and low-pass filters, respectively, as they "pass" signals higher than, or lower than, the filter setting. Theoretically, signals with frequencies below or above these points will be completely eliminated from the recording. We can create a bandpass filter by setting our LFF at 30 Hz and our HFF at 1000 Hz. This creates a bandwidth of 970 Hz; literally, the range of the frequencies between the low and high filters. Published

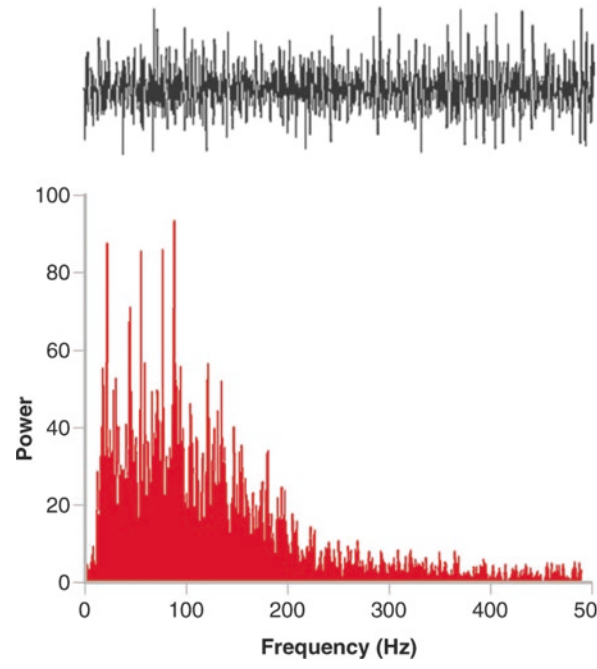

Fig. 4.5 An example of EMG firing is shown along the *top*. The signal can be deconstructed using statistical methods and displayed as a graph of the component signals of varying frequencies and their power. This example of surface EMG shows us that the majority of the signal power is contained at frequencies below 300 Hz. This knowledge is important when setting filters as it determines the optimal settings for low- and high-frequency filters

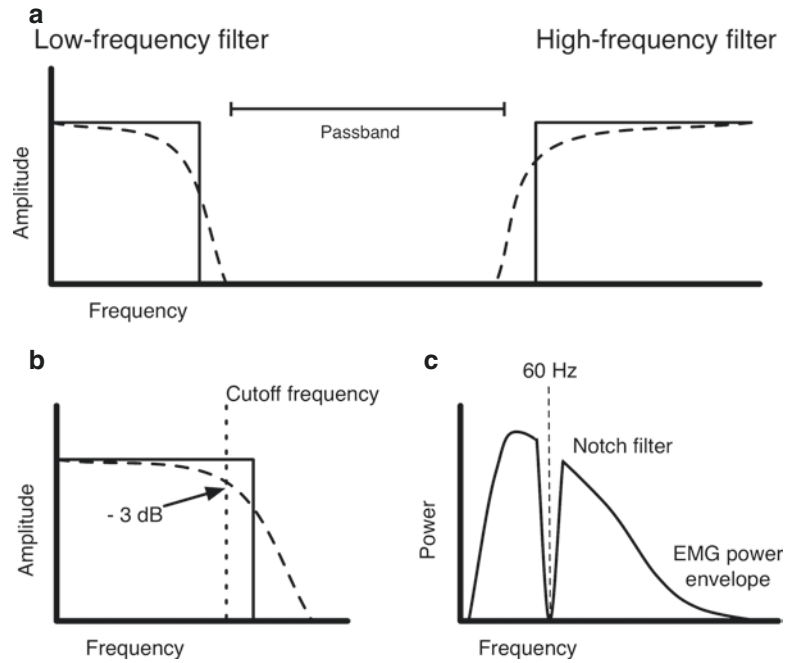

Fig. 4.6 Examples of common filter configurations are given. A passband is created in (**a**) in order to pass the desired frequencies while eliminating those above or below the selected range. The efficacy of filters is shown in (**b**) as the real filter performance (*dotted line*) deviates from the perfect orthogonal filter conception. Filter performance can be described by the cutoff frequency and the steepness of the slope. In (**c**), a notch or mains filter is shown against the envelope of signal power from a signal such as EMG. Although the notch filter can reduce unwanted 60 Hz noise, it can be seen that the filter eliminates all signals around the 60 Hz frequency. This represents a great deal of signal power from an EMG recording

guidelines exist regarding the typical settings for bandpass filters for common modalities in the surgical suite.

Notch Filters

In contrast to bandpass filters, notch filters, also referred to as band-stop filters, pass most frequency components of a signal while eliminating those in a specific range. Notch filters are designed to eliminate noise at a very small range of frequencies. The most obvious example of a notch filter is a 60 Hz filter, or a "mains" filter, designed to remove 60 Hz electrical noise from a recording. Notch filters are almost never applied to evoked potentials as they can cause a ringing artifact in the averaged recordings. Although they can be applied to spontaneous recordings such as EMG, they are generally discouraged as the EMG signal contains a great deal of power around the 60 Hz frequency (see Fig. 4.5). While the 60 Hz noise can be attenuated, the true signal in a critical portion of the power spectrum will also be lost. For this reason, it is preferable to remove the 60 Hz noise through physical methods rather than applying a notch filter. These methods include unplugging sources of electrical noise, relocating the recording instruments away from such sources if they cannot be unplugged, and ensuring that cables from the recording instruments cross power cables from other devices at perpendicular angles.

Efficacy (Roll-off)

Up to this point, we have been discussing filters as if they have the ability to perfectly eliminate unwanted frequency bands from our physiologi-

cal recordings. In practice, this is not the case as filters do not completely eliminate unwanted signals but merely attenuate them in a graded manner (see Fig. 4.6). The performance of this attenuation can be described by the cutoff frequency and roll-off. The roll-off is the slope of the frequency attenuation curve. The cutoff frequency of a filter is the point at which 30% or 3 dB of the energy of the signal has been removed. Roll-off describes how rapidly the power of the signal is attenuated beyond the filter cutoff. Steeper roll-offs are to be preferred as they indicate that the filter is acting in a more effective manner to attenuate the signal beyond the filter stop frequency. Although we tend to imagine filter cutoffs as being absolute points beyond which no signal is passed, it is important to understand the limitations of filter effectiveness when setting filter boundaries.

Digital Versus Analog Filtering

In clinical electrophysiology, we make use of both analog and digital filters. Analog filters are physical filters built into the circuitry, which permanently affect the signals being recorded. Analog filters are applied before digitization. The quality of analog filters depends upon the quality of their components and the manufacturer; they can suffer from imperfections arising from their physical construction. These include drift with changing time and temperature, nonlinearities in their function, and imperfect tolerances. In addition, analog filters can introduce a time distortion, especially in frequency components close to the filter cutoff. The introduction of a time distortion in certain components of the signal is referred to as a phase shift (Fig. 4.7). Low-frequency analog filters affect the slower frequency components of the signal (those closest to the low cutoff), causing them to appear earlier than faster components. This is known as a phase lead. High-frequency analog filters affect the higher-frequency signal components (those closest to the high cutoff), causing them to appear later than slower components. This is known as a phase lag. As a practical matter, phase shifts have little effect on the final signals so long as the filter settings are not adjusted during the course of a surgical procedure. The monitoring clinician in the surgical suite should understand that any changes in latency of evoked potentials following an adjustment of the LFF or HFF are likely the result of phase shifts. From this realization,

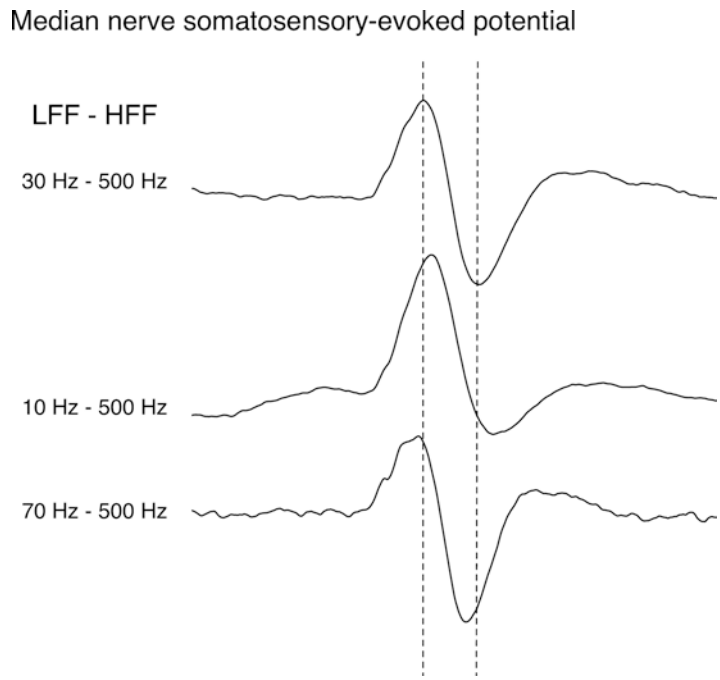

Fig. 4.7 A phase shift is demonstrated by altering the low-frequency filter settings for a median nerve somatosensory evoked potential. Adjusting the LFF to lower or higher settings causes a latency shift in subsequent recordings that could be misinterpreted as a cause for alarm

it should be obvious that filters should preferably be set at the beginning of a procedure and not adjusted thereafter lest a real change in signal latency caused by a true surgical event be misinterpreted as the result of adjusting filter settings.

Digital filters have gained in popularity in signal processing as they do not suffer from these inconsistencies. These filters can be used to remove unwanted low and high frequencies with a very effective cutoff and without introducing phase shifts. However, they do introduce a lag into the process as there is a tangible period of time required for the calculations involved in the digital filtering process. This lag has been reduced with increasingly powerful processors in the hardware systems used n for monitoring; however, these systems also introduce an added cost. In practice, digital filters are mostly applied in the surgical suite in the form of data smoothing operations.

Generally, analog filters are preferred for intraoperative monitoring as they are cost-effective and do not introduce a delay in signal processing. This is important as the interpretation of signals like EMG and EEG (electroencephalogram) need to be communicated in real time to the surgical staff. Digital filtering is typically applied post hoc and in a reversible manner, as in the case of smoothing filters. It is generally preferable to avoid the use of smoothing filters in reading neurophysiological signals, as an inherent error is introduced when digital filters are used. Nevertheless, reversible smoothing filters do not permanently degrade the signal data and may allow the monitoring clinician to capture monitorable data in very noisy environments. Circumstances exist where digital smoothing provides the only way to achieve monitorable signals.

Artifact Rejection

Artifact rejection filters are perhaps the simplest filters to conceive. They operate upon the principle that true neurophysiological signals are expected to be within a certain amplitude range. Anything exceeding this range can be eliminated from the signal as being noise. Artifact rejection filters are an example of digital filters that are applied after the differential amplification stage. They are applied to evoked potentials that are time-locked to a stimulus volley. The most common use of artifact rejection filters is during the collection of averaged evoked potentials, and the most common source of rejected signals is the use of electrocautery. The signal recorded during electrocautery is often contaminated with high-amplitude artifact and unrecoverable by other filtering methods. Moreover, the artifact is of such high amplitude that if only a few sweeps, of the hundreds that may be averaged together, were to contain the electrocautery artifact, the final averaged signal would be unmonitorable. As such, rejection of these high-amplitude signals must be undertaken in order to be able to monitor during periods of electrocautery. If artifact rejection is not to be used, the monitoring clinician in the surgical suite will be forced to cease monitoring evoked potentials during the use of electrocautery.

Averaging

Many of the neurophysiological signals recorded in the surgical suite are measured in microvolts. Even after amplification and filtering, the noise and other background signals recorded alongside the true signal of interest are considerably larger. As such, it cannot be expected that a single recorded sweep will yield a monitorable signal. The SNR of evoked potentials such as SSEPs can be improved greatly by a process known as averaging. Averaging works on the principle that the time-locked evoked potential present in each recording sweep will average together, creating a larger amplitude signal, while random background activity in each recording sweep should cancel, resulting in lower-amplitude background. The closer the background signals are to truly random signals, the more easily they will be averaged out. The improvement in the SNR resulting from signal averaging is quantifiable. The effectiveness of the averaging can be predicted by the formula $SNR_f = SNR_i \times (\text{sqrt}(n))$, where SNR_f is the final SNR (after averaging), SNR_i is the initial SNR, and n is the number of sweeps. For example, if

a single sweep has an SNR of 1:5, this can be improved to an SNR of 4:1 by averaging together 400 repeated sweeps (1:5 × sqrt(400) = 1:5 × 20 = 4:1). This improvement is most pronounced at lower numbers of sweeps. There is, in fact, diminishing return to increasing the number of sweeps. In the example described earlier, the SNR is improved by a factor of 20 with 400 sweeps. A further doubling of the number of sweeps to 800 will take twice as long to produce a signal but increase the SNR by only an additional 40%.

Stimulation Rates

For any evoked potential that is averaged, the opportunity exists to greatly attenuate the amount of noise that is averaged into the final signal by picking an optimal stimulation rate. In almost all cases, 60 Hz mains noise and various harmonics of this frequency will represent the greatest amount of steady-state noise experienced in the surgical suite and the greatest opportunity for improving SNR with optimal rates of stimulation. A harmonic is a frequency that is an integer multiple of the fundamental frequency. For instance, the third, fifth, and seventh harmonics of a 60 Hz noise will be 180 Hz, 300 Hz, and 420 Hz, respectively. These odd-ordered harmonics will almost always encompass the greatest amount of noise signal power. The noise encompassed in these frequencies can be averaged either in or out of the final averaged product. For obvious reasons we would prefer the latter. The first way to achieve this is to select a stimulus rate that is not a factor of the noise frequencies we experience in the surgical suite. A stimulus rate of 2 Hz, for instance, is a factor of 60 Hz and its odd-ordered harmonics. Selecting this stimulus rate will result in averaging a great deal of electrical noise into the final signal, most likely rendering it unmonitorable. On the other hand, a stimulus rate of 3.17 is not a factor of 60 or its odd-ordered harmonics and will result in a much better SNR of the final averaged signal. However, we can continue to improve our SNR if we select a stimulus rate that is an integer factor of the noise frequency + 1/2 period. To determine this, we simply divide the noise frequency by the stimulus rate. If we want to evaluate 3.17 as a stimulus frequency, for instance, 60/3.17 = 18.93. Although 3.17 is not a factor of 60, it is still suboptimal for our purposes as it is not equal to an integer factor + 1/2 period. On the other hand, if we evaluate 4.44, 60/4.44 = 13.51. The result is an integer factor of 60 + 0.51 (close to 1/2 period). A stimulus rate of 4.44 Hz then will average out a larger portion of the 60 Hz noise present in the recorded signal. We can create a simple chart that will predict the optimal stimulation rates to be used in the surgical suite in the presence of 60 Hz noise and the third-, fifth-, and seventh-ordered harmonics thereof. As we can see from Table 4.1, the stimulus rates of 2.18, 2.79, and 4.44 Hz are best optimized to average 60 Hz and odd-ordered harmonic noise out of the signal. These stimulus rates should be the first choice when running averaged evoked potentials that require a relatively low stimulus rate, such as SSEPs.

Digitization

Thus far we have concerned ourselves with analog signals. Analog signals have the properties of being continuous and having an infinite number of points in the signal. Furthermore, an analog signal is a recorded signal that is directly proportional to the underlying physiological phenomenon. As such, the signal is analogous to the physiological phenomenon. Digital signals, on the other hand, are a sampled representation

Table 4.1 The optimal stimulation frequencies for use while averaging out 60 Hz noise and its associated third-, fifth-, and seventh-ordered harmonics

Stim frequency	60 Hz	180 Hz—third	300 Hz—fifth	420 Hz—seventh
2.00	30.00	90.00	150.00	210.00
2.18	27.52	82.57	137.61	192.66
3.17	18.93	56.78	94.64	132.49
4.44	13.51	40.54	67.57	94.59

The poorest options are factors of 60 such as 2 Hz stimulation that will actually average noise into the recording. The most optimal stimulation frequencies can be divided into 60 and its ordered harmonics and will be ½ period off of a real integer

of the analog signal, created by quantizing the signal at discrete points in time. Digitization is necessary in order to import the signal into a computer for analysis. Humans tend to prefer to view data in analog form as waveforms or lines. As pattern-detecting creatures, we have an affinity for viewing changes in data in this visual manner. Computers, on the other hand, are suited to mathematical analysis of the data and require a discrete set of numbers in order to apply mathematical operations and analyze the data.

Digitization is performed through the use of an analog-digital converter (ADC). It is important that digital representations of analog signals be as faithful to their analog templates as possible. The process of digitization involves both sampling and quantization. Put simply, sampling is the process of describing the signal as a set of discrete time periods, equal in length, over the whole signal. Quantization is the process of assigning a discrete amplitude value to the analog signal at each one of these time points. Digital signals must be accurately resolved or represented in both the horizontal (time) and vertical (amplitude) domains. Improper sampling or quantization will yield a final produce that has been corrupted and is invalid.

Sampling

Digital signals are resolved in the horizontal or time domain with a fidelity that is proportional to the sampling interval. The sampling interval is merely the time between each sample that is extracted from the analog signal. The inverse of the sampling interval is the sampling frequency in Hz. For instance, a sampling interval of 1 ms would yield a sampling rate of 1000 Hz. This simply means that we are extracting a data point from the analog signal 1000 times each second. Sampling and digitizing an analog waveform at a higher frequency results in a sampling of a greater number of points and a more accurate digital representation of the signal. However, it also requires greater computer power and memory capabilities. Sampling at too low a frequency will result in a failure to accurately resolve the signal on the horizontal axis. This process is known as aliasing.

Nyquist Theorem

Therefore, what frequency is appropriate for sampling a given signal? The Nyquist theorem states that in order to avoid aliasing, it is necessary to sample at a frequency that is twice the highest frequency component of the analog signal. While the Nyquist theorem represents the minimum sampling frequency to avoid aliasing, the optimum sampling frequency is three times the highest frequency component of the analog signal (Fig. 4.8). As mentioned before, neurophysiological signals collected in the surgical suite have previously determined frequency boundaries, beyond which no useful signal exists. For instance, the majority of the signal

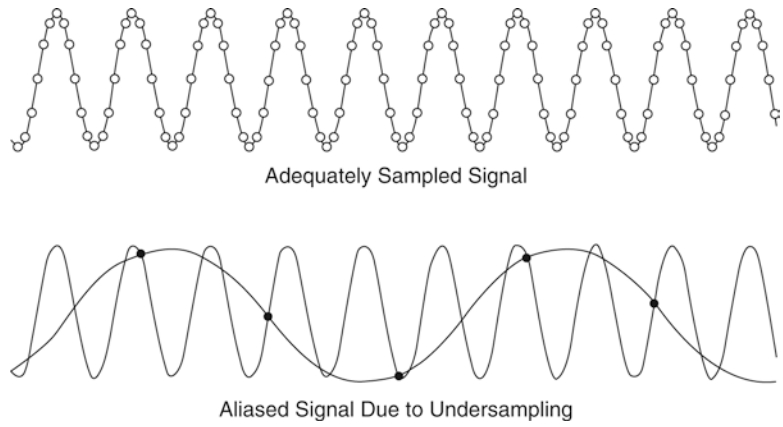

Fig. 4.8 The *top* figure was sampled at a high rate (*closed circles*), and the resulting waveform identically overlays the original. In the *bottom* example, the sampling rate was insufficient to create a high-fidelity digital signal. A curve connecting the samples creates a low-fidelity digital waveform

power derived from a surface EMG recording is gathered at 300 Hz or less. By applying the Nyquist theorem, we can see that a minimum sampling rate to digitize this signal without aliasing would be 600 Hz, although 900 Hz would be optimal.

Quantization

Once the signal has been sampled, we must then undertake the process of quantization. This is the assignment of amplitude values derived from the analog signal at each time point. Note that this process involves some level of error as an analog signal with an unlimited set of values must now be represented by a digitized signal with a discrete set of values. The factor that limits accuracy of the final signal in this process is the number of bits available in the ADC. The number of discrete data points available is represented as 2^n, where n is the number of bits. For example, an ADC with 4 bits can be used to represent 16 unique values, while an ADC with 8 bits can be used to represent 256 unique values. Obviously, an ADC with a greater number of bits will allow a greater range and a greater resolution in our final digitized signal. The resolution that we apply will determine the accuracy limits of our newly digitized dataset. If the vertical resolution is too limiting, our data will be clipped, as some of the values will fall outside of the range we have created. For instance, if we set a vertical range of ±10 μV, and the analog signal reaches 25 μV, this portion of the signal will be lost. On the other hand, if the vertical resolution is too large, our dataset will be lacking in accuracy as a small range of values will have to represent the entire amplitude of the analog signal. We will lose resolution as a small range of signals must be represented by a broad range of values.

Consider Fig. 4.9 and notice that the first part of the signal, the M-wave, has been clipped, while the second part of the signal, the F-response, is displayed with a rather small amplitude. This is the trade-off that occurs during quantization when selecting an input range or vertical resolution. If we optimize the range for the M-wave in this recording, the F-response will be too small to detect. On the other hand, if we optimize the range for the F-response, we will clip the M-wave, as has occurred in this example. In this case, a compromise was chosen so that the F-response could be viewed along with the M-wave; it was appropriate to clip the M-wave

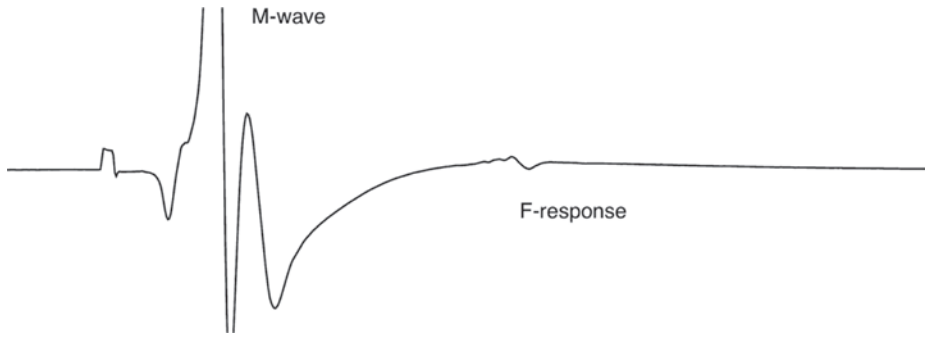

Fig. 4.9 A representative example of a recording made in the surgical suite is shown. The first portion, marked M-wave, has been clipped as some of its values fall above and below the range of the recording. The second part of the recording, marked F-response, is a very small amplitude response and is difficult to display with the range so broad. This is a visual representation of trade-offs that must be made in the quantization process. Having an ADC with a high bit count can help to alleviate this problem as the dynamic range of the recording is increased so that high- and low-amplitude recordings can be resolved together

portion in order to view the F-response properly. This is a visual representation of what happens when the vertical resolution is suboptimal.

Concluding Thoughts on Recording

Recordings made in the surgical suite must accurately represent the true bioelectrical activity of the structures that are generating the signal. Advancing technology has given us the ability to make high-quality digital recordings in an electrically hostile environment with a minimum amount of difficulty. Although our current instrumentation eliminates the need for us to perform tedious calculations and continuously alter our stimulation and recording parameters, it is no less necessary for the modern physiologist to have a complete understanding of the concepts behind electrophysiological stimulation and recording.

Review Questions

1. What are the possible consequences of using excessive analog filtering on neurophysiological signals?
2. Discuss sampling bias. How this can be overcome?
3. What is the effect of averaging on small amplitude signals? What do you think is sacrificed for the benefit seen with increased signal sampling?
4. Why is the careful selection of stimulus frequency important?

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5 Anesthesiology and Intraoperative Electrophysiological Monitoring

Tod Sloan and Alan David Kaye

General Overview: Anesthesiology as the Practice of Perioperative Medicine

The role of the anesthesiologist during procedures where intraoperative electrophysiological monitoring (IOM) is being performed involves anesthetic titration, attaining physiological homeostasis, and medical management of the patient. Further, the anesthesiologist participates in mitigating neural injury when the monitoring indicates that the nervous system may be at risk for injury. More specifically, the choice of anesthetic agents directly impacts the ability to reliably record IOM responses, the physiological management (e.g., blood pressure) impacts on the reserve of the nervous system to tolerate procedural trespass. When altered responses indicate the health of the nervous system may be compromised, the insights of the anesthesiologist and the ability to improve the physiologic reserve are keys to reducing neurologic risk. This chapter is written to discuss these aspects to improve integration of the anesthesiologist into the IOM monitoring team effort.

Preoperative Planning

It should be noted that the role of the anesthesiologist extends throughout the peri-procedural period. Often referred to as the "internist in the operating room," anesthesiology is the practice of medicine which extends before and after the procedure. In the pre-procedural period the anesthesiologist partners with the surgeon, the patient's usual health care provider, and if warranted, consultants to insure that the patient is in optimal shape in order to best tolerate the procedure with minimal overall health risk. The anesthesiologist evaluates those medical conditions that impact directly on intraoperative management to understand their pathophysiology and preoperative management so that this can be extended through the peri-procedural period. In particular, evaluations are very important regarding the management of cardiac, pulmonary, hepatic, renal, and pregnancy-related issues and specific medications taken by the patient. These conditions will also result in each patient being classified by the American Society of Anesthesiology (Table 5.1)

T. Sloan (✉)
University of Colorado, Department of Anesthesiology, Aurora, CO, USA
e-mail: Tod.Sloan@UCDenver.edu

A. D. Kaye
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

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Table 5.1 American society of anesthesiologists physical status classifications[a]

1. A normal healthy patient
2. A patient with mild systemic disease
3. A patient with severe systemic disease
4. A patient with severe systemic disease that is a constant threat to life
5. A moribund patient who is not expected to survive without the operation
6. A declared brain-dead patient whose organs are being removed for donor purposes
If Emergency – add "E" (e.g., 2E)

[a]From http://www.asahq.org/Home/For-Members/Clinical-Information/ASA-Physical-Status-Classification-System

and impact medication choice, which may force challenges and potential compromises with a typical anesthetic regimen for IOM.

Other pre-procedure considerations include: assessment of the airway, positioning-related factors, intravenous access, pathophysiology of the surgical site, fluid management, and other issues which may impact on anesthesia medication choices for the procedure and management in the immediate recovery period (e.g., post-traumatic stress, trauma, elderly considerations, chronic alcoholism, or chronic opioid use are some examples). Airway issues, including anticipated difficult intubation or an unstable cervical spine, are extremely important and dictate an awake intubation or other alternative induction and advanced airway intubation methods. As such, the choice of muscle relaxants and sedative drugs may differ. As an example, the lack of intravenous access may necessitate an inhalational agent induction as is often used in children. Another example would be inducing anesthesia for a patient with increased intracranial pressure. In this case, the blood pressure must be maintained high enough to preserve adequate cerebral perfusion pressure. Hence, in general (unless central venous pressure is extremely elevated), the net perfusion of the brain (cerebral perfusion pressure) is the mean arterial pressure minus the intracranial pressure (discussed along with other physiological relationships later in the chapter).

In the preoperative period, the anesthesiologist will usually discuss the planned procedure with the surgeon or proceduralist. Positioning, anticipated blood loss, special procedures (such as deliberate hypotension or hypothermia), and anticipated procedure risks are discussed to plan for anesthesia management and the preparation of ancillary equipment. This is also a time when the IOM team should confer with the surgeon to insure the optimal choice of monitoring modalities. Additionally, a discussion between the entire team is warranted when surgical cases arise that require the IOM team. The anesthesiologist, the IOM team, and the surgeon should communicate before induction regarding optimal anesthetic choices in order to facilitate that monitoring and this communication is a standard of care to ensure the optimal patient outcome. In particular, the discussion between the IOM team and anesthesiologist should identify when the initial baselines need to be acquired, especially immediately post intubation or prepositioning, so that the induction can be planned with this consideration. It is important to recognize that the final choice of anesthetic medications may be a compromise between that which may appear optimal to the IOM team and that which may be dictated by medical and patient considerations identified preoperatively. Not infrequently, this discussion may result in a bargaining where the best compromise can be made. Once baselines are acquired, the anesthesia choice may be further adjusted based on how the patient is responding vis-à-vis hemodynamics and IOM.

Preoperative Discussion with the Anesthesiologist

The discussion with the anesthesiologist must take into consideration the experience and training of the specific practitioner since they may need to consult with a colleague. The anesthetic is usually delivered and monitored by either a solo practitioner or by an "anesthesia care team." Solo practitioners include physician anesthesiologists or certified registered nurse anesthetists (CRNA). The care team model includes an in-room practitioner such as a CRNA, anesthesia resident physician trainee, student registered nurse anesthetist (SRNA), or an anesthesia assistant (AA) *with* anesthesiologist oversight. Physician anesthesiologists are individuals with a medical degree (MD or DO)

who have completed a focused residency in anesthesiology and may have advanced training (fellowship) in subspecialty areas (e.g., neurosurgical, thoracic, cardiac, pediatric, or obstetric anesthesia). A CRNA is an advanced practice nurse with a master's degree who has undergone specific training in anesthesia after nursing practice, typically in intensive care environments and may work with a physician anesthesiologist or, in some circumstances, as a solo practitioner. Some CRNAs may have advanced degrees such as a doctorate in nursing practice (DNP). An AA has a masters level education with specific anesthesia training in the classroom and practical course work. They can act as physician extenders who always work under the direction of physician anesthesiologists. Since their background, training, and experience will vary, each of these individuals may be familiar with the anesthesia considerations for IOM so preoperative discussion, especially the day before the procedure if possible, will be important for their planning.

Types of Anesthesia

Important for discussion with the anesthesiologist is to understand the terms used with regard to the delivery of anesthesia (in particular the two ways the term "MAC" is used). First, although general anesthesia is usually used with IOM, anesthesia is also delivered in other ways. "Local MAC" is used to describe the use of intravenous medications (e.g., propofol, midazolam, etc.) in patients where local anesthesia is used (often by the surgeon or proceduralist) to anesthetize a limited region of the body. In this case, the term "MAC" stands for "monitored anesthesia care" and should not be confused with the similar term "MAC" used to describe the potency of inhalational anesthetics (see below). One of the goals of an anesthetic medication is sedation and usually amnesia. Blocking of noxious stimuli (such from the procedure) is primarily done by the use of local anesthesia. IOM is usually not utilized with monitored anesthesia care; however, electrocorticography and mapping of the motor and speech cortex is done by a specialized form of MAC when patients have "awake" craniotomies where local anesthesia is used on the scalp to allow a craniotomy (the exposed brain is insensitive) [1].

"Regional" anesthesia is used to describe the delivery of anesthesia where only a part of the body is made completely insensitive to the surgical stimulation. For example, the patient may have local anesthesia injected to anesthetize specific nerves or plexus (such as a brachial plexus block anesthetizing an arm) or injected into the spinal or epidural space ("neuraxial" anesthesia). Similar to local MAC, sedation may be such that the patient becomes responsive to stimuli in a continuum from awake to unresponsive. Intravenous medications are used to produce sedation and usually amnesia. Blocking of noxious stimuli (such as from the procedure) is primarily done by the regional blockade. IOM is usually not possible with the regional blockade of major neural structures as the local anesthetics used usually render the neural structures unable to conduct IOM signals. However, when regional anesthesia is conducted to anesthetize regions allowing access to structures for a procedure and the neural structures being monitored are not anesthetized, IOM can be used as long as the IOM technique is not painful. A good example is the use of electroencephalography during carotid endarterectomy where a cervical plexus regional blockade is often used to allow surgical access to the carotid artery.

General anesthesia (GA) is the anesthesia usually used during most procedures where IOM is used. Typically, several medications are used together to produce a more comprehensive anesthetic, which involves four major anesthetic goals. First, medications are given to produce a state of unconsciousness where the patient does not respond to stimuli. Second, medications are delivered to ensure that the patient has no awareness or recall (amnesia) during the procedure. Third, the anesthesia medications are used for analgesia and to block noxious stimuli from activating the nervous system. This goal is often termed anti-nociception and differs from Local MAC and regional anesthesia where local or regional anesthesia is primarily responsible for

this aspect. Preventing awareness and recall is a major concern of anesthesiologists and is a major concern in designing an intravenous anesthetic.

Fourth, medications are used in GA to block movement (e.g., muscle relaxation) of the patient in response to stimuli. Although this can be accomplished using medications which block transmission at the neuromuscular junction, the anesthetics used for most cases where IOM is performed involve using agents to block the reflex transmission of sensory stimuli through the spinal cord producing peripheral motor activity. This reflex pathway involves afferent sensory input from the periphery, synaptic connections within the spinal gray matter, efferent motor pathways, and descending influences from the brainstem and cortex.

It is important to differentiate the reflex movement through the spinal cord pathways in the anesthetized, unconscious patient from the voluntary movement of an unanesthetized, awake patient. The comment "the patient is awake" when they move under anesthesia is usually incorrect since the motion is due to reflex activity in the inadequately anesthetized spinal cord from peripheral stimuli. This need for immobility is one of the major challenges and concerns for the anesthesiologist during procedures involving IOM when complete muscle relaxation must be avoided. The challenge for the anesthesiologist is that parts of the same pathway are used for reflex movement and for desired muscle activity from transcranial motor cortex stimulation (MEP). This suggests that the titration of effect in the efferent components (spinal gray matter and peripheral nerve) must be a delicate balance to facilitate the MEP but inhibit the reflex activity. This also stresses the need for good antinociception at the spinal level to further block the afferent limb of the reflex movement pathway.

Each of these anesthetic goals can be accomplished using a mixture of agents acting at different neural sites. It is currently believed that anesthetic agents act through their interaction with specific synaptic receptors. The two major categories of action include facilitating the inhibitory effect of gamma-amino-butyric acid (GABA) by actions at the GABAa receptor, and the inhibition of the major excitatory synapse at the N-methyl-D-aspartate (NMDA) receptor [2]. Other synaptic targets include the neuronal acetylcholine receptor (nACh), the mu opioid receptor, central alpha2 receptors, and the potassium, calcium and glycine channels [2]. Drugs differ by respective major synaptic targets as well as different subunits of the receptors and the distribution of these receptors throughout the central nervous system. As such, the anesthetic plan is usually developed taking into consideration these goals, the procedural goals (including IOM), and the specific medical issues for each patient. The plan is usually designed for the different phases of general anesthesia: premedication, induction, maintenance, emergence, and recovery.

Phases of Anesthesia

Premedication is the use of medications, usually prior to bringing the patient to the procedure room, to begin an anesthetic effect. Frequently, the patients may receive a small dose of midazolam which contributes to sedation and amnesia. Patients may also receive a short-acting analgesic, such as an opioid, if they are having pain and long-acting analgesics (often non-opioids) to provide postoperative pain reduction, especially in patients with chronic pain. Other medications may also be given to produce various pharmacologic effects such as anti-emesis or antibiotics to reduce perioperative infection. In general, these medications usually have minimal effects on IOM.

Induction is the phase of anesthesia after the patient is brought to the procedure room and basic anesthesia monitoring established (e.g., electrocardiogram, blood pressure, temperature, and pulse oxygen saturation). The doses of induction medications are rather large because of the needed initial cortical and brainstem drug effects, hence the loss of the cranial nerve-mediated blink reflex to eyelash stimulation is used to identify adequate brainstem drug effect. They also serve to load the patient with medications to start accomplishing the anesthesia goals and cover the gap until the maintenance medications

are established. Unless an awake intubation or an inhalational mask induction is planned, induction usually includes a sedative drug like propofol, an opioid, and a muscle relaxant to facilitate intubation. These bolus doses would normally preclude IOM monitoring during induction; however, the time needed to establish IOM is such that most of the effects of the induction drugs will resolve except for muscle relaxant effects if longer acting agents are chosen.

If an awake intubation is chosen, the doses of sedative agents and opioids are usually smaller such that a clinical neurological assessment is often possible, and IOM can be established sooner. Generally, muscle relaxants are not needed for an awake intubation but topical application of local anesthetics to the airway may preclude assessment of electromyography of the vocalis muscle.

If an inhalational "mask" induction is chosen, the patient is asked to breathe sevoflurane with or without nitrous oxide. After the patient is asleep and an intravenous line established, the sevoflurane can be reduced and the anesthetic converted to the desired maintenance agents. Since the dose of sevoflurane is rather large, IOM will be affected until the agent has been reduced in the nervous system, which will be somewhat longer than the decrease of the concentration in the breathing circuit as shown on the anesthesia monitoring systems.

Once induction is accomplished, anesthesia is converted to the *maintenance phase*. Two basic types of anesthetic agents are used for maintenance: inhalational and intravenous. Further, combinations of agents are often used in order to accomplish the four main anesthetic goals described above. The choice of these agents has a major impact on IOM such that the integration of patient needs, procedure needs, and IOM considerations must be balanced. During the maintenance phase, slow changes in IOM are typically observed. Although referred to as "anesthetic fade" this may relate to a variety of pharmacologic and other factors [3].

At the conclusion of the maintenance phase is *emergence*. This is the period when the anesthesia is reduced until the patient awakens and is extubated. This requires the resumption of spontaneous breathing and the return of protective airway reflexes. The goal is to have the patient safely awaken so they have a stable physiology and can be transferred to the care of a nurse in the recovery phase in the postoperative care unit. Aside from insuring adequate pain relief and minimizing the chance of nausea and vomiting, the major goal is having the patient awaken promptly to allow a neurological examination to identify problems. Since intravenous anesthetic agents may take longer to eliminate than inhalational agents, the intravenous agents may be reduced during the latter part of the maintenance phase, often after the conclusion of the procedure and during the closure of the wound, which may result is some associated IOM changes.

Specific Anesthesia Drugs Used for Maintenance

Based on the synaptic targets involved with individual agents, each anesthetic agent contributes differently to the four goals of anesthesia. For example, at clinically (or surgically) equivalent depths of anesthesia, some agents may produce a different spectrum of cortical or spinal cord evoked potential depression than other agents. The differences between drugs may be explained by differing profiles on receptor types (e.g., GABA, NMDA, etc.), differing location of drug action (i.e., pre- or post-synaptic effects), the effects on individual subtypes of these receptors, and the anatomic distribution of the receptors and subtypes. The differences between drugs also contribute to different profiles of drug action on monitored responses.

Halogenated Inhalational Agents

The halogenated inhalational anesthetic agents (isoflurane, sevoflurane, desflurane) are the most frequently utilized agents in GA when IOM considerations are not present. These drugs have a broad action on neural structures with excellent cortical effects on actions of unconsciousness

and amnesia (action at the GABAa receptor), excellent spinal cord effects leading to immobility (effect at the glycine receptor), some contribution to antinociception (actions at the NMDA, nACh, sodium, and potassium channels), and some muscle relaxation effects (from action at the nACh receptor in the neuromuscular junction). These actions make them very versatile agents that provide excellent coverage for amnesia and immobility which are major concerns of anesthesiologists.

These agents are modern relatives of ether that are liquids which can be vaporized and mixed into the anesthetic breathing circuit for delivery to the patient. They are relatively inexpensive and very easy to deliver and adjust. Aside from physical-chemical characteristics, the three currently commonly used agents differ in their potency, solubility in the body, and pungency. Their potency is typically measured by the minimal alveolar concentration in the lung where 50% of subjects move (and the other 50% don't) to a painful peripheral stimulus. This value, in volume %, is termed "MAC" and typical values are shown in Table 5.2. Of note, these values decline with age such that a given concentration may have a more profound effect in older individuals. There also are several states, conditions, and medications that can increase or decrease MAC requirements (e.g., chronic alcoholic increases MAC, pregnancy decreases MAC, etc.).

In general, since the different agents act through similar neural mechanisms, the agents are thought to be equivalent when compared at concentrations of similar MAC value. Hence, 1 MAC of Desflurane is considered approximately equivalent to 1 MAC of Sevoflurane such that substituting one for the other (such as for pungency or solubility) should have similar effects.

Table 5.2 Properties of inhalational anesthetics

Agent	Adult MAC (vol%)	Blood: gas partition coefficient
Isoflurane (Forane®)	1.15%	1.4
Sevoflurane (Ultane®)	2.1%	0.68
Desflurane (Suprane®)	6%	0.42
Nitrous oxide	105%	0.46

Data taken from [4, 5]

The second property, solubility in tissues, is the basis for the time it takes to raise and to lower the anesthetic effect in the body. This is reflected in the blood: gas partition coefficient, where a higher coefficient is a more soluble agent (see Table 5.2). Although raising and lowering depends on the mechanics of the breathing pattern and cardiac output, a drug which is least soluble (e.g., desflurane) has its concentration in the brain rise the quickest and reduces the quickest when the delivery is stopped. For this reason, many anesthetists favor desflurane (quickest) or sevoflurane (second quickest) over isoflurane (least quick) when wanting to use an agent with IOM that might need to be eliminated because of excessive IOM effects.

Finally, pungency is the property of irritation of the lung when breathing the agent. Of these agents, sevoflurane and nitrous oxide are the least irritating so that if anesthesia needs to be induced by having the patient breathe the agent (i.e., there is no intravenous line), sevoflurane (with or without nitrous oxide) will be the choice. Isoflurane and desflurane are simply too irritating to be practical for mask induction.

Since the halogenated agents have broad actions at many synaptic targets, they provide a model for understanding the effect of anesthetic agents on IOM modalities. In summary, since the effects occur at synapses, the location of synapses in the IOM pathway will help explain the resultant effects [6].

As such, the somatosensory evoked potential (SSEP) has minimal anesthetic effects on the responses recorded form the peripheral nerve and spinal cord since the first synapse is located at the cervical-medullary junction. Since a second synapse is located at the thalamus and the remainder in the primary sensory cortex, the most prominent anesthetic effects will be on responses recorded from the cortex. This is shown in Fig. 5.1. Of interest is that the change in cortical amplitude is nonlinear similar to the "on-off" nature of the anesthetic effect on consciousness. This is consistent with an anesthetic effect producing a blocking of sensory transmission through the thalamus

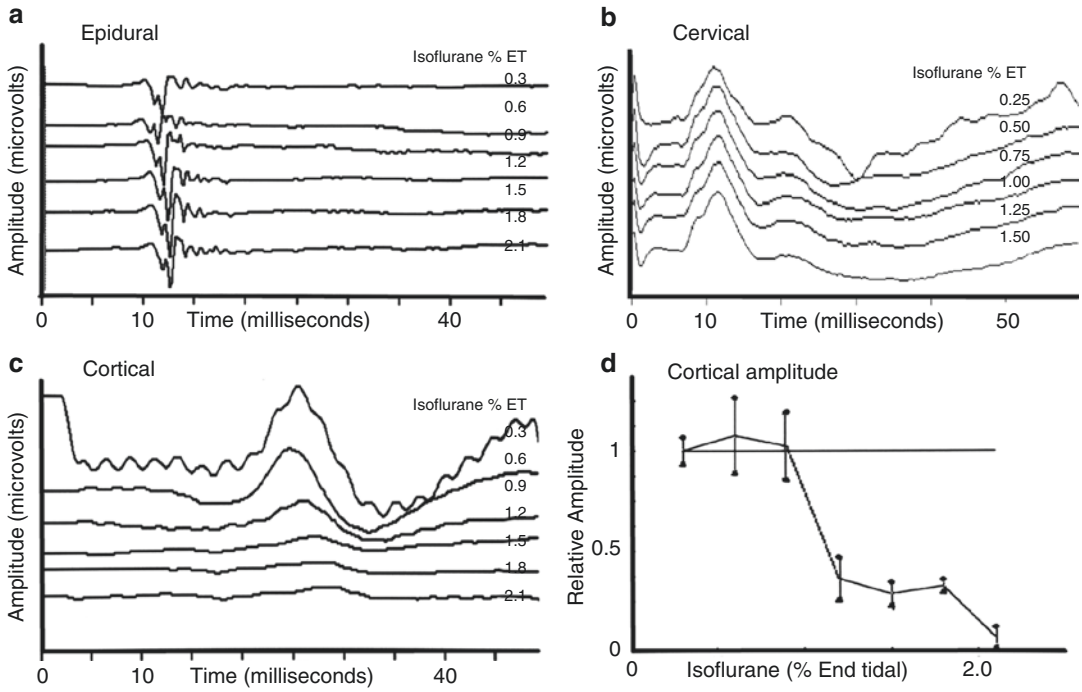

Fig. 5.1 Effect of isoflurane on SSEP recordings. Changes in lower extremity somatosensory evoked potentials recorded at several locations with increasing concentrations of isoflurane in the baboon. (**a**) Shows recordings from the epidural space that indicates minimal effects. (**b**) Similarly shows minimal effects in the response recorded over the cervical spine. (**c**) Shows a prominent effect on the response recorded over the somatosensory cortex. (**d**) Shows a plot of the amplitude of the cortical response demonstrating a nonlinear amplitude reduction as the isoflurane concentration is increased. (Reproduced with permission from Sloan [6])

as postulated by John in his theory of anesthetic action [7]. This is consistent with the practical observation that the inhalational agents must be limited to 0.5–1 MAC in order to monitor the cortical SSEP. Since patients will vary with their actual anesthetic effect (50% will be higher or lower than the average MAC), this "on-off" concentration may be higher or lower than reflected in the average value. Further, some pathologic processes may predispose the patient to a more profound effect suggesting some patients may not have recordable IOM responses with any concentration of the agent.

The cumulative anesthetic effect of halogenated anesthetics on synapses is also seen with the brainstem auditory response (Waves I-V), which show a progressive increase in effect as the number of synapses increases along the auditory pathway (V > III > I) (Fig. 5.2). Also similar to the SSEP, the cortical auditory response (mid-latency auditory evoked potentials, MLAEP) is markedly affected. The effect on the cortical visual evoked response is also substantially consistent with the multiple synapses involved in the cortical response.

The location of synapses in the motor pathway is consistent with the dramatic anesthetic sensitivity of transcranial motor evoked potentials. Since these responses are elicited by direct stimulation of the motor cortex which produces a "D" wave recorded near the spinal cord and no synapses are involved, the D wave is resistant to increasing doses of halogenated agents (Fig. 5.3). However, since the "I" waves recorded near the spinal cord are produced by transsynaptic stimulation in the motor cortex, their loss is consistent with the anesthetic effect on cortical synapses (see Fig. 5.3).

The second location of synapses in the motor pathway is in the spinal cord gray matter where

descending motor pathways activate peripheral motor nerves. At this location the number of synapses varies with the specific muscles; however, the more proximal muscles have more synapses suggesting why the more distal muscles in the limbs may provide the best-recording sites during anesthesia.

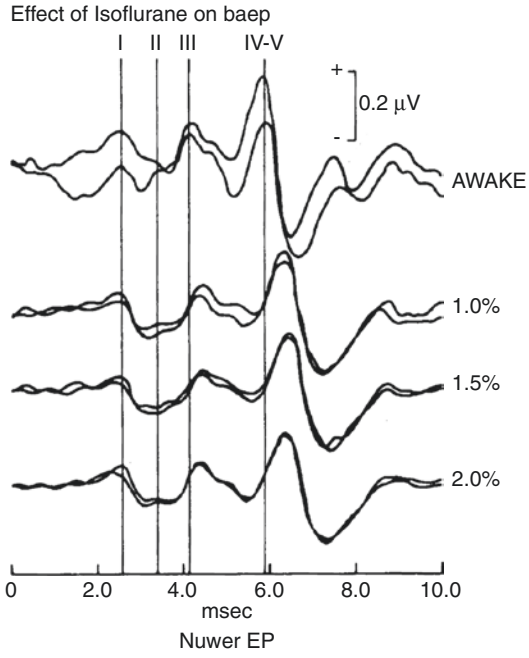

Fig. 5.2 Effect of isoflurane on auditory brainstem response. Influence of isoflurane on auditory brainstem response (ABR). Latency of peaks III and IV-V are progressively increased with increases in isoflurane. The effect on IV-V is more than on III. (Reproduced with permission from Manninen et al. [8])

The production of peripheral motor responses results from the cumulative effect (temporal summation) of D and I waves and anterior horn cells. As such, the loss of I waves explains why the single pulse transcranial stimulation of the electrical or magnetic technique is so exquisitely sensitive to anesthesia and why the high-frequency multipulse technique is more successful since it produces multiple D waves that can summate more successfully. However, anesthetic effects at these spinal gray synapses can block the production of peripheral motor responses. In addition, a variety of other descending tracts (descending suprasegmental systems [corticospinal, rubrospinal, vestibulospinal, and reticulospinal systems] and propriospinal systems) influence the excitability of the anterior horn cells such that anesthetic effects on these pathways may also hamper the production of muscle responses. Thus, the cumulative effect of the cortical and spinal synaptic effects may explain why the muscle responses from transcranial stimulation are so easily affected by anesthetic agents.

It is of interest to note that the effects of the anesthetic agents on the spinal gray matter forms one of the anesthetic challenges for the choice

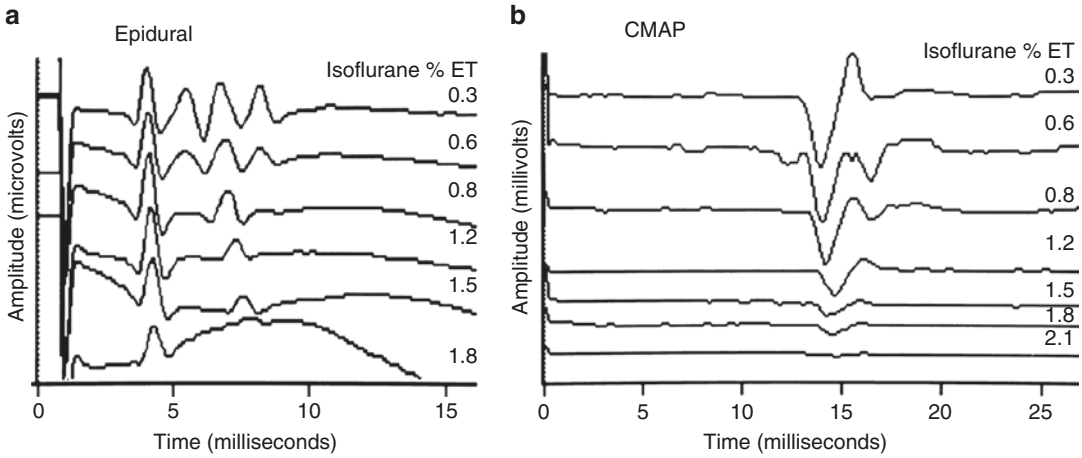

Fig. 5.3 Effect of isoflurane on motor evoked potentials. Changes in transcranial motor evoked potentials recorded in the epidural space (**a**) and in compound muscle action potentials (CMAPs) in the hand (**b**) in the baboon. Shown is the maintenance of the single D wave ("D") and loss of the multiple I waves ("I") in the epidural recording and loss of the CMAP response with increasing concentrations of isoflurane. (Reproduced with permission from Sloan [9])

of agents. Clearly, the ability of a descending motor pathway impulse to produce a motor nerve response or the muscle response follows the same pathway which needs to be blocked to prevent patient movement in response to peripheral noxious stimuli such as surgery. Thus, a balance of effects is needed and contributions of anesthetic agents, which block noxious stimuli coming into the spinal cord, are important to block the reflex pathway leading to immobility. Perhaps the profound effect of the halogenated agents on the reflex activity mediated through the glycine channels explains why this balance is difficult to achieve in their presence.

Similar to the SSEP, the MEP response also shows a nonlinear loss over a narrow anesthetic concentration. This means that some individuals will have muscle responses that can be acquired with 0.5 MAC of an inhalational agent, but most will require a careful titration of intravenous agents (TIVA). For these many reasons, the anesthetic effects on the motor pathway make the muscle responses of the transcranial motor evoked potential one of the most difficult monitoring techniques under anesthesia.

The anesthetic effect of the halogenated agents in the spinal cord accounts for the depression of the H reflex. Studies of the anesthetic effects on the H reflex show that it parallels the movement to noxious stimuli used to measure MAC of the halogenated agents. Thus the anesthetic effects on the motor evoked potentials will mirror the effects on the H reflex [10].

There is one additional synapse in the motor pathway located at the neuromuscular junction. Although the inhalational agents do have effects at this location, the effects do not appear to be clinically significant in the absence of neuromuscular blocking agents (NMBA). However, the effect of the NMBAs is known to be amplified by halogenated inhalational agents such that the NMBA management must be carefully monitored in their presence such that the motor response is not excessively depressed. Fortunately, the only anesthetic agents that impact the muscle responses from peripheral nerve stimulation are neuromuscular blocking agents and local anesthetics blocking conduction in the nerve.

In summary, the halogenated inhalational agents have a broad spectrum of anesthetic effects (i.e., multiple synaptic targets) that provide excellent cortical effects on consciousness and amnesia, and excellent effects on the spinal gray matter producing immobility such that they are superb anesthetics when IOM is not being utilized. Since they have less profound antinociception, they are often supplemented with opioids creating what is often termed a "balanced" anesthetic. However, because of the profound depression of the SSEP and MEP, these halogenated agents must often be restricted or avoided during IOM and other agents utilized.

Nitrous Oxide

Nitrous oxide is also an inhaled agent. Nitrous oxide (N_2O) is different from the halogenated agents consistent with anesthetic action at different synapses. N_2O is particularly effective in antinociception due to its action at the NMDA receptor with additional actions at the mu opioid, nACh, and potassium channels. In addition, it contributes to unconsciousness and amnesia through minor actions at the GABAa and central alpha2 receptors and contributes to immobility through minor actions at the glycine receptor [11]. In summary, it has excellent qualities in blocking noxious stimuli but weak properties in producing cortical effects (unconsciousness and amnesia) and immobility. This makes it a nice complement to the halogenated agents and explains the logical combination of the two classes in general anesthesia.

The effects of nitrous oxide on the SSEP and MEP are similar to the halogenated agents. However, the potency of N_2O (MAC >100%) limits this effect. When compared at equi-MAC anesthetic concentrations, nitrous oxide produces more profound changes in the muscle recordings of motor evoked potentials than the halogenated inhalational anesthetic agents [12]. Some studies have suggested that similar to low concentrations of the halogenated agents, nitrous oxide may be acceptable for MEP monitoring with multipulse stimulation techniques; however, the other anesthetics used with it make a difference

in the degree of depression [13–15]. As such, if only one inhaled agent is to be used many anesthesiologists would prefer the contribution of the halogenated agents to the cortical and immobility effects rather than the contribution of nitrous oxide to antinociception (which could be accomplished using opioids with less impact on the responses).

Unfortunately for IOM, the combination is synergistic such that the depression of the combination is more profound than would be predicted by the effect of the individual agents [16]. Thus, it is not recommended to use a combination of halogenated agents and nitrous oxide with IOM.

Intravenous Anesthetic Agents

Since the inhaled agents may need to be reduced in concentration (or avoided) in some patients during some IOM modalities (notably transcranial motor evoked potentials and cortical somatosensory evoked potentials), anesthesia maintenance may require the use of intravenous anesthetic agents since these are often more compatible with accomplishing the four anesthesia goals and facilitating IOM. The intravenous agents are usually chosen such that the mixture of agents accomplishes the goals of anesthesia while minimizing the impact on the IOM responses. When general anesthesia is provided solely by intravenous agents it is termed total intravenous anesthesia (TIVA).

Agents Used to Produce Unconsciousness and Amnesia

One key class of intravenous agents is those which contribute effectively to unconsciousness and amnesia. Referred to as sedative, hypnotic, and amnestic agents, these include propofol, etomidate, dexmedetomidine, and midazolam (Table 5.3).

Table 5.3 Commonly used sedative, hypnotic, and amnestic intravenous agents

Agent	Trade name
Propofol	Diprovan®
Etomidate	Amidate®
Dexmedetomidine	Precedex®
Midazolam	Versed®

Propofol

Of these agents, propofol is currently the most commonly utilized sedative and amnestic agent. Propofol has potent effects via actions at the GABAa receptor which increases the inhibitory effects of GABA, acts at extrasynaptic GABA receptors and has some action at neuronal nACh receptors. This action at the GABAa and minor effects at the glycine receptor in the spinal cord contributes to immobility during anesthesia. Finally, it makes minor contributions to antinociception through minor actions at the glycine and nACh receptors. At the spinal cord level, the dose-response curve for reflex movement is substantially flattened compared to the halogenated agents such that a dose can usually be found that provides adequate suppression of movement without the depression of the MEP seen at higher doses [17].

Propofol does have depressant effects similar to the halogenated inhalational agents. For this reason (as with all anesthetic agents) a constant infusion is required to prevent sudden changes in drug concentration that depress the IOM responses simulating neural compromise. Usually, a dose can be chosen which produces the desired anesthetic effects without excessive depression of the IOM responses.

At higher doses it will block the responses such that if they are needed for an individual patient, other agents may need to be added to accomplish the cortical effects and reduce the propofol dosage. One of these agents is ketamine which is discussed below [18]. A second, less commonly used agent is an infusion of lidocaine which also reduces the dose of agents used for

antinociception [19, 20]. A newer version of propofol named fospropofol does not appear to have any advantages over propofol [21].

Propofol is used as a common induction agent for anesthesia (usually in doses of 1–2 mg/kg). With TIVA, the initial bolus dose is needed to get the blood level up to the needed dose so that a subsequent infusion can keep the needed effect level. That infusion is designed to match the metabolism or clearance of the drug so that a constant drug level is maintained to provide the needed level of anesthesia and a constant level of drug effect on the monitoring. In general, this infusion rate will vary with the patient needs but is usually 120–180 micrograms per kilogram per minute when it is used solely with an opioid in TIVA. The infusion may be higher in patients who need a higher effective blood level because of drug tolerance from preoperative medication usage, or maybe lower when other medications are added to the TIVA that also provide some sedative-hypnotic effects (e.g., inhalational agents or lidocaine infusions). As with all of the anesthetic agents, a constant level is important to minimize acute changes in the monitoring. Slow awakening can often be seen with prolonged infusions due to increasing context-sensitive half-time so decreasing the infusion rate near the end of the procedure may be used.

Etomidate

An alternative sedative/hypnotic to propofol is etomidate, which also has potent effects on unconsciousness and amnesia via actions at the GABAa receptor. An advantage is that etomidate has limited cardiopulmonary depressant effects and has a role during induction in selected patients. It contributes to immobility via actions at the GABAa and glycine receptors and has some minor contributions to antinociception through actions on the potassium channels. Many practitioners have avoided etomidate in infusion over time because of concerns of worsened outcome in patients with sepsis secondary to the depression of corticosteroid production in the adrenal gland [22, 23].

Etomidate is unusual because at clinically useful doses it enhances the EEG and increases the amplitude of both sensory and motor evoked responses [24–29]. This enhancement may produce seizures in patients with epilepsy; the combined effect of enhanced activity of epileptic foci and transcranial electrical stimulation is unknown [30].

Etomidate is delivered like propofol in bolus doses for induction and by infusions for TIVA. Its use for induction as a bolus (typically 0.2–0.3 mg/kg) is often favored in patients who may be dehydrated, in the elderly, have poor myocardial function, or who may be hemodynamically unstable because it has less depressant effects on the heart. Like propofol, the induction bolus can achieve effective blood concentration so that a subsequent infusion can maintain the effective level for anesthesia. At present, infusions of etomidate in TIVA are limited as indicated related to adrenal suppression. Current research with chemical relatives (e.g., methyl-carbonyl etomidate) may hold promise for an alternative without adrenal depression in the future [21].

Benzodiazepines

Prior to the introduction of propofol (and prior to MEP monitoring), an infusion of midazolam was used with TIVA [25, 31]. The benzodiazepines, notably midazolam, also act at the GABAa receptor producing amnesia at doses that are not associated with unconsciousness. This produces a mild depression of cortical SSEP and as a premedicant or occasional supplement in anesthesia allows MEP recording [28, 31–36]. In addition to possible cortical locations for the benzodiazepine effect, an effect at the spinal cord has been described as antinociceptive through actions at the GABA receptors in lamina I and II in the dorsal horn [37, 38].

The superb anxiolytic and amnestic qualities make midazolam an excellent addition to anesthesia but a prolonged drug half-life makes it less favorable than propofol for a TIVA infusion-based anesthetic. As such midazolam is frequently given preoperatively for reduction of anxiety (anxiolotic) and as a method to help insure amnesia when concerns are raised about the possibility of awareness. These small doses, given intermittently, do not appear to have a detrimental effect on monitoring; however, higher doses have been associated with MEP depression. It is also an excellent agent to add at the end of a procedure if delirium on awakening is anticipated or to mitigate hallucinatory effects of ketamine (see below).

Dexmedetomidine

One of the newer additions to the sedative agents is dexmedetomidine which acts as a central, selective alpha2 adrenoreceptor agonist drug. It has been shown to reduce the amount of propofol, opioids, and halogenated inhalational agents needed during maintenance [39]. The sedative drug effect is primarily due to action in the brainstem (locus coeruleus) which decreases cortical arousal influences producing sleep similar to normal sleep. Although not FDA approved at present for use in general anesthesia, it is approved for sedation in the intensive care unit where patient awakening allows a less effected neurological exam. Of note, it does not appear to have amnestic action. Side effects of hypotension and bradycardia occur because of effects on the brainstem limit the drug to a role as a supplement to other anesthetic agents.

Dexmedetomidine has "opioid-sparing" properties and appears to be an excellent supplement in the opioid-tolerant patient. The effects on SSEP recordings are minimal but, as with propofol, higher blood levels of dexmedetomidine (or when moderate dosages of other agents such as propofol are used with dexmedetomidine) inhibit MEP monitoring making its use challenging [40, 41].

Dexmedetomidine is not used as a sole agent in TIVA for two reasons. First, its dose is limited because it reduces the sympathetic influences from the brainstem which results in bradycardia and hypotension. Second, at acceptable doses, it does not produce adequate antinociception and amnesia, so these effects must be provided by other medications. Hence, TIVA can be accomplished by dexmedetomidine infusion supplemented by low dose propofol for amnesia and an opioid infusion for antinociception. Alternatively, a low-dose inhalational agent may be used instead of the propofol to provide the amnestic action. Often these combinations will be acceptable for SSEP recording but, if higher doses of dexmedetomidine or propofol are used, MEP monitoring may not be possible.

Barbiturates

Although not fully explored, infusions of methohexital (Brevitol®) have been used during IOM [42]. This may be a viable alternative if the other agents are not usable.

Intravenous Agents Used to Block Noxious Sensory: Antinociception

Intravenous agents must also be chosen to block noxious sensory stimuli. These drugs will assist in immobility by blocking the afferent limb of spinal reflex activity if the agents work at the spinal cord as well as reducing sensory stimuli to the brainstem and cortex which increase the need for sedative and amnestic agents. The primary agents used with TIVA include the opioids and ketamine, although dexmedetomidine and lidocaine infusions also contribute to the antinociception (Table 5.4) [43].

Table 5.4 Commonly used intravenous agents for antinociception

Agent	Trade name
Fentanyl	Sublimaze®
Sufentanil	Sufenta®
Remifentanil	Ultiva®
Ketamine	Ketalar®

Opioid

Infusions of opioids have mild effects on evoked responses while producing excellent antinociception by actions in the dorsal horn of the spinal cord, at multiple sites in the cerebral cortex and brainstem, and in the rostral ventromedial medulla which is responsible for a descending modulatory system which modulates processing of noxious stimuli in the dorsal horn. The naturally occurring opioids (e.g., morphine) have some sedative properties; however, the agents usually used with anesthesia (fentanyl, sufentanil, remifentanil) do not have significant sedative or amnestic properties. As such, opioids (e.g., fentanyl, sufentanil, remifentanil) form an important component of TIVA as they can have mild effects on monitored responses. Opioids can potentiate the effect of propofol and suppress motor reflexes and spontaneous activity. In addition, bolus doses of these agents will produce a transient depression of responses, and higher concentrations can persistently produce significant depression such that delivery of the opioid by infusion is important during anesthetic maintenance similar to the use of infusions of agents for unconsciousness and amnesia [44]. Unfortunately, opioids do not produce unconsciousness or amnesia and may be less effective in opioid-tolerant, chronic pain patients.

Ketamine

As an alternative or supplement to the opioids, ketamine has very potent antinociceptive actions via its action at the NMDA receptor. Ketamine is also thought to act by inhibition of the neuronal nicotinic acetylcholine receptors, decreasing the presynaptic release of glutamate, and through opioid-like actions on the opioid receptors. Ketamine can be particularly effective in the opioid-tolerant patient.

In addition, it contributes to unconsciousness and amnesia via minor actions at the GABAa receptor. Like etomidate, ketamine is an excitatory agent and has been reported to increase cortical SSEP amplitude [45, 46], increase the amplitude of muscle and spinal recorded MEP responses, and increase the H-reflex [47–49]. Because it has cortical effects, ketamine can be added to an intravenous technique to enhance the antinociceptive effect while allowing reduction of agents which produce the depression of the evoked responses such as when high doses of propofol would otherwise be needed. Unfortunately, increases in intracranial pressure in patients with cortical abnormalities or hallucinatory activity limit its usefulness. The latter effect can lead to a delirium on emergence with subsequent unfavorable effects similar to post-traumatic stress. The latter can be minimized by avoiding ketamine during the conclusion of the procedure (which may lead to an amplitude reduction of the SSEP and MEP) or the utilization of midazolam at awakening. Fortunately, the hallucinatory effect of ketamine in children is less than in adults making it a common choice in children. As such, ketamine is often given early in a procedure (such as at induction), by intermittent boluses, or by a low-dose infusion with avoidance of the drug during the last hour of the procedure.

Lidocaine and Magnesium

An additional agent that is re-emerging as a supplement to provide antinociception is intravenous lidocaine. At the low-dose infusion used with TIVA it contributes to sedation, antinociception, and immobility in TIVA. As such it reduces the doses of propofol and opioids needed [50–52]. It is postulated that the cortical actions occur primarily by potentiating GABAergic acting agents and NMDA antagonism [50, 53–55]. The contribution to antinociception is thought to occur at the spinal cord and cortical levels with the antinociceptive action contributing to immobility by blocking the afferent noxious stimuli.

Similar to lidocaine, infusions of magnesium have been utilized but not fully explored for IOM [56].

Agents Used for Immobility

As indicated above, the agents used for antinociception, unconsciousness, and amnesia also have effects at the spinal cord level reducing the afferent sensory limb or reflex arc in the spinal gray matter leading to immobility. Achieving this delicate balance is one of the major challenges with TIVA; a sufficient mix of effects blocking the afferent sensory information and blocking of the reflex motor pathways is needed to avoid excessive effects on either which could prevent successful motor evoked potential monitoring.

Neuromuscular Blocking Agents

A second method of producing immobility is the use of neuromuscular blocking agents to reduce transmission across the neuromuscular junction. As mentioned above, these agents are often used to facilitate intubation at induction and may be requested during certain procedure periods such as during abdominal exposure of the spine or during the separation of the posterior musculature from the spine during a thoraco-lumbar corrective surgery. If neuromuscular blockade is utilized during the portion of the procedure where IOM using muscle responses is desired, a carefully controlled infusion producing a partial neuromuscular blockade is needed.

However, their use during intraoperative electrophysiological monitoring (IOM) using muscle-derived responses (e.g., spontaneous and stimulated electromyography [EMG] and muscle responses to transcranial motor evoked potentials [MEP]) are controversial because they can reduce the amplitude of the responses and simulate the loss of neural function. The partial neuromuscular blockade also increases the needed stimulation intensity for MEP monitoring which could result in the stimulation of the corticospinal tract being below the motor cortex. This could render MEP monitoring ineffective for monitoring the motor cortex. Hence many individuals recommend their avoidance during the monitoring portion of procedures [57, 58].

These agents block transmission across the neuromuscular junction by interfering with the action of acetylcholine (ACh) released from the presynaptic terminal in response to the depolarization of the peripheral nerve [59, 60]. Currently, the commonly used NMBAs include succinylcholine, vecuronium, rocuronium, and cisatracurium (Table 5.5). Succinylcholine is referred to as a "depolarizing" agent because it stimulates a muscle contraction before blocking ACh action. It is usually rapidly metabolized by plasma cholinesterase which gives rise to its short duration of action (except in a few patients where inherited abnormalities in the enzyme lead to prolonged action up to 4–6 hours) [61]. Many anesthesiologists consider succinylcholine the best agent for intubation with an anticipated awkward intubation or where the patient may regurgitate gastric contents on induction.

The depolarizing effect of succinylcholine leads to two undesirable side effects. First, the muscle contractions may lead to unpleasant muscle pain postoperatively. This can sometimes be reduced with pretreatment of a small dose of a non-depolarizing agent (e.g., rocuronium). More importantly, the depolarization leads to a potassium efflux that is normally of no consequence, but can be life-threatening (e.g., cardiac arrest, lethal arrhythmia) in some circumstances such as recent spinal cord, neuromuscular disease, or crush injury. Increases in intraocular and intracranial pressure can be seen with succinylcholine. Also, it can trigger malignant hyperthermia (as can inhalational agents) in the rare susceptible

Table 5.5 Drug doses and effects of commonly used neuromuscular blocking agents

Drug	Intubating dose (mg/Kg)	Onset (min)[a]	Duration (min)[b]
Succinylcholine	(Anectine®) 1	1	10
Cis-atracurium	(Tracurium®) 0.1	2.5	45
Rocuronium	(Zemuron®) 0.6	1.3	33
Vecuronium	(Norcuron®) 0.1	3	33

[a]Time to 95% depression of a single muscle response to supramaximal stimulation of a nerve

[b]Time to recovery of the single response to 25% of the unblocked response

patient where its use is contraindicated (if known through family history or testing). This inherited condition results in excessive muscle hyperactivity with the massive release of calcium from the sarcoplasmic reticulum, which is associated with hyperthermia, muscle breakdown, and consequent life-threatening metabolic derangements which demand immediate cooling and treatment with dantrolene.

The other neuromuscular blocker agents are referred to as non-depolarizing because they occupy the postsynaptic Ach receptor, competitively blocking neuromuscular transmission without causing initial muscle activity. These agents also interact at a presynaptic receptor which reduces the availability of stored Ach leading to reduced Ach release with closely timed stimulation [62, 63]. This latter effect leads to the "fade" seen in the train of four, where each successive response is smaller. The effect of these drugs is terminated through metabolism by the liver and kidney except for cis-atracurium which undergoes spontaneous chemical decomposition ("Hoffman elimination"), making it useful when hepatic and renal function is limited or non-existent [64]. In general, these agents have a slower onset and longer duration of action than succinylcholine but have pharmacokinetics suitable for use by infusion. In general, if an NMBA is needed for intubation, succinylcholine or rocuronium are often chosen to minimize the time to subsequent acquisition to IOM baselines that involve muscle activity.

If needed, the neuromuscular blocking effect of non-depolarizing agents can be reversed and this typically occurs at the end of a surgical case. The common method of reversal involves increasing the released amount of acetylcholine by preventing its metabolism by an acetylcholinesterase inhibitor (e.g., neostigmine [prostigmin®]). This agent is administered with an antimuscarinic agent (glycopyrrolate or atropine). Cholinergic receptors are both nicotinic and muscarinic and unopposed increases in acetylcholine with an acetylcholinesterase inhibitor will help overcome the competitive nondepolarizing blocker; however, there will also be a muscarinic effect, including the potential for bradycardia and even asystole. This reversal can only be effective if the level of the blockade has reduced such that the higher amounts of acetylcholine can effectively compete for action at the receptors [65]. Hence, one or more responses in the train of four need to be present before the reversal will succeed, which correlates to no more than 2/3 of acetylcholine receptors being blocked (see below). If it is available in the operating room, a novel cyclodextrin drug which sequesters rocuronium (sugammadex) may allow reversal of a more profound blockade, without the potential for cardiovascular effects as seen with acetylcholinesterase agents.

Although many practitioners recommend avoiding neuromuscular blockade when IOM techniques utilize muscle responses, the partial neuromuscular block has been used. A partial blockade must be titrated in a carefully controlled infusion. The monitoring of the effect is normally done using "train of four" paradigm where the EMG response of a muscle is measured following four supramaximal stimulations of a peripheral nerve at 2 Hertz. This produces a progressive reduction of muscle responses (fade) in the train of four such that a reduction in the size of the fourth response (T4) to the first response (T1) is seen (train of four ratio) that is related to the degree of blockade [66]. Additional blockade cases a reduction in the number of responses until all are gone. The degree of blockade can sometimes be assessed when no responses are present by counting the number of "post-tetanic" responses occurring at one-second intervals following a 5-second tetanic stimulation [67].

Monitoring of the train of four in muscles used for IOM is important because the NMBA can cause different degrees of blockade in different muscles and the muscles chosen by the anesthesiologist may not represent those used for IOM [67]. For example, the most peripheral muscles (hands and feet) are blocked at drug levels below that which block more proximal and truncal muscles. The diaphragm requires the highest drug level such that a patient may be breathing or coughing when distal muscles are completely blocked. As the blockade resolves this, and other differences in muscle sensitivities, gives way to a non-uniform resolution of blockade stressing the

need to monitor TOF individual muscles involved in monitoring to be sure the individual muscle status is known. Further, a variety of factors can alter the usually expected response to NMBA. These include hypothermia and a variety of medications, including anti-epileptic agents [67].

When neuromuscular blockade is utilized, MEP and muscle responses secondary to cranial nerve or peripheral nerve stimulation have been successfully monitored when the train of four has two responses [67, 68]. When monitoring is being utilized to detect nerve irritation by mechanical or other non-electrical stimuli the amplitude of the response will be reduced by the blockade but no studies have been done to clarify the exact reduction or any recommendations for acceptable neuromuscular blockade. Hence, in these circumstances, many individuals recommend avoiding neuromuscular blocking agents.

Physiological Management

The anesthesiologist monitors and manages the physiology of the patient. Often the management maintains the patient physiological parameters in their normal range. The various monitors used can be helpful to the IOM team to determine physiological factors that may be contributing to alterations in the IOM responses. Sometimes the physiology is intentionally altered (e.g., deliberate hypotension or deliberate hypothermia). Blood pressure management is particularly important as it is a major determinant of tissue blood flow. In normal tissue cerebral and spinal cord blood flow is thought to be "autoregulated" such that over a range of blood pressures the blood flow is maintained constant. Mean pressures below the "lower limit of autoregulation" result in below normal blood flows which may compromise tissue flow if it is below the normal margin of safety. In the past this lower limit was thought to be 60 mmHg, but a reappraisal of the studies has suggested it is variable and a more representative average value is 70 mmHg with some patients having lower limits above that level [69–71].

This autoregulation has been used to support the use of deliberately lowering the blood pressure (deliberate hypotension) so as to reduce the blood loss during spine surgery or reduce the risk of intracranial aneurysm rupture. In many patients, particularly young healthy patients, this lowering has been conducted with no significant risk to the spinal cord or brain. However, if the nervous system becomes compromised (e.g., ischemia), or the patient autoregulates at higher pressures (such as a patient with hypertension), the patient may require a higher pressure to insure adequate blood flow and health. Hence excessive hypotension can lead to ischemia and SSEP changes have been observed at blood pressures which would not ordinarily be associated with neural ischemia (e.g., systolic blood pressures above 90 mmHg systolic). Hence, changes in the SSEP and MEP may signal the need to raise the blood pressure such that the monitoring may help the anesthesiologist adjust the blood flow to reduce the neurological risk [72–75]. In addition to global hypotension, regional hypoperfusion (e.g., obstructed artery to a limb), hypoxemia, severe anemia, excessive hyperventilation, and reduced neural perfusion pressure (e.g., raised intracranial or cerebrospinal fluid pressure) can lead to ischemia.

With respect to blood pressure and blood flow, it is important to note that patients may have regions of poorer perfusion or vascular anomalies that can compromise blood flow. For example, the cortical regions at the boundaries of the anterior, middle, and posterior cerebral arteries are more sensitive to reductions in arterial pressure that the misled of the vascular regions (especially the triple boundary zone at the junction of the three regions). Similarly, the low cervical-high thoracic region of the spinal cord is another "watershed" area which has a precarious blood supply at the boundary of perfusion from the vertebral and cervical arteries and from the more caudal segmental radicular perforators from the aorta. This region has been known to become ischemic with excessive flexion of the neck in the sitting position. Finally, normal variants of the vasculature may not be known in individual patients (e.g., interruptions in the circle of Willis

in the brain and variations in the location of the artery of Adamkovich or segmental spinal perforators from the aorta to the spinal cord) such that monitoring may assist in identifying unexpected central nervous system ischemia.

The effect of blood pressure and ischemia on cortical and spinal cord neural tissue also includes a time element. As shown in Fig. 5.4, as cerebral blood flow falls below normal (50 cc/min/100 gm.), tissue blood flow does not fall until about 18–20 cc/min/100 gm. indicating a normal margin of safety in the brain. Below this level, the electrical activity becomes abnormal and absent at 12–15 cc/min/100 gm. corresponding with the blood flow reduction is an increased risk of neural injury which has a time element. This, at blood flows where the electrical activity is altered it may take 3–4 hours before a permanent neural deficit occurs. The time to injury becomes shorter as the blood flow is reduced further. Hence the loss of electrical activity is an early warning sign when ischemia is occurring and usually signals the desirability of maneuvers to increase blood flow. Hence it is quite common for the anesthesiologist to increase the blood pressure to improve tissue flow when the evoked responses are altered.

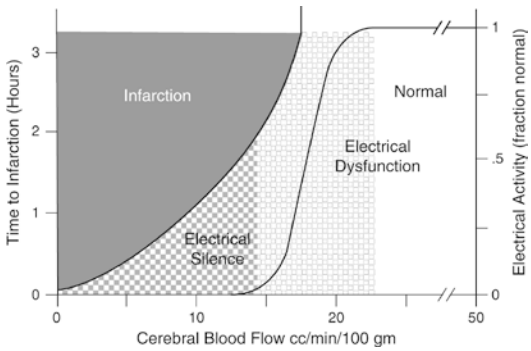

Fig. 5.4 Interaction of cerebral blood flow, electrical activity, and time to infarction. Depiction of electrical activity and the occurrence of irreversible cell death (infarction) as cerebral blood flow is reduced from normal (50 cc/min/100 g). As shown, the EEG becomes abnormal below 22 cc/min/100 g and absent when blood flow reaches 15 cc/min/100 g. Infarction occurs at 17–18 cc/min/100 g after 3–4 h and at progressively shorter periods when blood flow is below this level. (Reproduced with permission from Sloan and Jameson [76])

Body temperature is commonly below normal in the colder climate of procedure rooms. The associated cooler temperatures of the central nervous system can also alter IOM resulting in increases in latency and decreases in amplitude of evoked responses. Like reduced blood flow, hypothermia can also be regional (e.g., a cold limb from rapid infusion of cold fluids or cold spinal irrigation fluids). Although excessive hypothermia has adverse consequences (e.g., increased operative bleeding, postoperative infection, and cardiovascular complications), it is usually not directly detrimental to the nervous system. Changes in other physiological variables may produce alterations in the evoked responses during surgical monitoring. These include oxygenation, ventilation, and other factors which alter blood flow or the neural environment. As such, the monitoring conducted by the anesthesiologist can be invaluable to understand global physiological factors which may contribute to and help reduce neural compromise. When regional physiological effects intervene it may take a concerted effort to identify and correct these factors.

Positioning Considerations

The anesthesiologist also participates in the positioning of the patient for surgery. Occasionally adverse circumstances may result from positioning that is otherwise thought to be adequate or when the procedure results in a change in position leading to neural compromise. Changes in IOM responses may signal a possible compromise leading to a reappraisal and adjustment of the positioning. The procedure team (including the anesthesiologist) actively participates when positioning issues are raised.

Perhaps the most common positioning concerns are raised with the upper extremity where the brachial plexus and peripheral nerves may be stretched or compressed leading to IOM changes. For example, in the supine position the arm tucked at the patient's side may be pulled toward the feet to improve radiographic images of the lower cervical spine. This may also be coupled with tilting of the head away from that shoulder

for better surgical exposure. These positions may stretch the brachial plexus across the head of the humerus or stretch the cervical roots at the spine. With the arm out on an arm board or tucked at the patient's side, concerns are also raised about the ulnar nerve at the elbow from direct pressure on the ulnar nerve and median nerve in the antecubital space from extension of the arm, especially in individuals with muscular arms. When tucked at the side, the sheets used can form a tourniquet or exert direct pressure on the arm similar to the effect of a blood pressure cuff that does not inflate adequately. When out on an arm board, the brachial plexus can be stretched on the head of the humerus by a surgical member or fluoroscopy equipment by pushing the arm excessively toward the head of the table or if the arm falls toward the floor. Finally, peripheral neural compromise can result from infiltrated intravenous lines (including a compartment syndrome) or a hematoma from an arterial line.

In the prone position, many of the considerations mentioned above also apply. Elevation of the arm above the plane of the body or forcing the arm toward the head of the table can stretch the brachial plexus over the head of the humerus. The ulnar nerve is also at risk from excessive flexion of the arm at the elbow.

Unfavorable positions for the lower extremity appear to be less common but pressure on the peroneal nerve can occur in the lateral position. In some procedures (e.g., anterior lumbar spine procedures) and those where cannulas are placed in the femoral artery (e.g., procedures on the thoraco-abdominal aorta) a reduction in blood flow to the leg may be confused with neural compression.

Several potential neural compromises are associated with procedures in the sitting position. These include considerations for arm position as noted above, lateral compression of the peroneal nerve from the Mayfield head holder bracket. Monitoring of blood pressure in the extremity when a patient is in the sitting position can provide artifact, with each centimeter of distance from the level of the brain reflecting a difference in true cerebral blood pressure of about 1.3 mm of Hg due to the difference in density of water (approx. 1 gram per cm^3) and mercury (13.52 gram per cm^3) such that for every centimeter of height correlates with 1.3 mm of mercury. As with any position, neck flexion or extension can lead to spinal cord compression and IOM changes in patients with cervical spine pathology and spinal ischemia in the cervical-thoracic watershed region as mentioned above.

The myriad of positioning-related contributions to IOM changes far exceeds these more common circumstances. Hence, when IOM changes occur it is important to work with the anesthesiologist to determine if there are position-related issues that could potentially lead to neural injury and interrupt monitoring of the procedure. In addition, resolution of the IOM changes allows the IOM techniques to resume monitoring of the procedure.

Choice of Agents for IOM

As indicated above a large variety of considerations must be taken into account for the induction and maintenance of anesthesia during procedures where IOM techniques are employed. During the maintenance phase the anesthesiologist must consider (1) means to accomplish the anesthesia goals of unconsciousness, amnesia, immobility, and antinociception, (2) accommodating the individual patients medical and physical needs, (3) considering of the effects of anesthesia on the physiology of the patient, (4) meeting the needs of the surgeon or proceduralist, and (5) trying to provide a favorable environment to facilitate the IOM monitoring. Usually, this will entail a mixture of agents delivered by constant infusion so that fluctuations do not mimic neural compromise.

The considerations for anesthesia with respect to IOM revolve around the techniques employed. In general, the modalities can be divided into four categories based on their sensitivity to inhalational agents and sensitivity to muscle relaxants. When more than one modality is used, the effects of the agents must be considered on all of the techniques used.

Those modalities which are insensitive to inhalational agents and muscle relaxants allow

the anesthesiologist to choose any of the usual anesthetic agents. These techniques include auditory brainstem responses, peripheral nerve and spinally recorded SSEP responses, and D wave monitoring from transcranial motor cortex stimulation. Interestingly, reduction in muscle tone with neuromuscular blockade may improve the recording of the subcortical SSEP or other areas where underlying muscle activity is reduced.

Those responses that are sensitive to muscle relaxation, but are insensitive to inhalational agents, include the monitoring of peripheral and cranial nerve responses to stimulation or non-stimulated irritation. With the exception of the muscle relaxant considerations, inhalational agents and other anesthetic agents are acceptable. As noted, limited partial neuromuscular blockade may be acceptable with some of the stimulated techniques but patients with very small amplitude responses and non-electrically stimulated responses may not be recordable with partial blockade. If partial neuromuscular blockade is used the challenge for the anesthesiologist is to maintain a stable degree of blockade.

Those responses which are insensitive to neuromuscular blockade but sensitive to inhalational agents include the cortically recorded sensory responses of the SSEP. In these patients, the primary consideration will be restricting the use of inhalational agents such that adequate amplitude responses are present for monitoring. As mentioned, the effect is a nonlinear response with some patients tolerating as much as 1 MAC of inhalational agent and others tolerating little if any agent. In general, since many of these patients tolerate ½ MAC this dose is often initially chosen using insoluble agents (e.g., desflurane or sevoflurane) that can be eliminated if needed [77]. Since ½ MAC is usually insufficient for anesthesia, infusions of a sedative/amnestic (e.g., propofol) and an opioid is often chosen. In some of these patients, an adjunctive agent (ketamine, dexmedetomidine, and lidocaine) may also be used with or instead of the other intravenous agents. In the net, the tolerance of the neural pathways to cortical depression and the cumulative stimulation and depression of the cortically acting agents determines if the response can be monitored. For these responses, the anesthesiologist can use NMBA which helps to ensure that immobility is not a problem.

The most restrictive modalities include the transcranial motor evoked responses because they limit the use of inhalational agents as well as the neuromuscular blocking agents. As such, IOM often requires a total intravenous anesthetic using only mixtures of sedative/amnestic agents and opioids. In these cases, the major challenge (and concern) of the anesthesiologist is to maintain immobility and insure amnesia.

Some adjunctive agents are often helpful (e.g., ketamine) and others appear to be frequently incompatible with recording (e.g., dexmedetomidine). Some patients will tolerate a small dose of inhalational agent (e.g., ½ MAC) but, not infrequently, a pure TIVA will be needed. Of note, the effect of the inhalational agents is nonlinear such that a large drop in amplitude may occur over a small increase in concentration and that threshold varies among patients. Hence each patient needs to be evaluated individually. In addition, the effect of the agents may change with time as the effect site concentration changes (the intravenous agents in particular) such that a decline in amplitude may occur over time (e.g., this may be the explanation for a time-related "fade" of responses) [3].

Since multimodality monitoring has become standard in most procedures and since motor evoked potentials have become a commonly used technique, total intravenous anesthesia has become a common choice. As eluded to above, some patient variability in the responses will influence the choice of TIVA components and whether a small dose of inhaled agent (e.g., ½ MAC) may be acceptable. In general, very young children (especially under age 2) have incompletely developed nervous systems and therefore are extremely sensitive to anesthetic agents, particularly inhalational agents. In this case a TIVA technique, often supplemented with ketamine, will be needed for adequate IOM, especially with the use of MEP. In these patients, methods to prime or enhance the motor responses may also be needed (e.g., double burst stimulation or peripheral sensory or motor system priming).

Older age children, especially adolescents, often have robust IOM responses and frequently tolerate supplementation of a TIVA technique with ½ MAC inhalational agent for motor or sensory monitoring. If the child is neurologically normal this supplementation is often done initially with the caveat that it may need to be eliminated. However, if the neurological exam reveals compromise, it may be better to identify the baselines without the inhalational agent with its addition occurring after good responses are identified.

Adult patients often have less robust responses than adolescents because aging and the effects of medical comorbidities have an impact (e.g., diabetes, vascular disease). Although many adults with normal neurological exams will tolerate ½ MAC inhalational agent, those with myelopathy, weakness, numbness and tingling may not. In these patients, baselines with SSEP and MEP are often acquired before the effect of the inhalational agent is assessed. If the responses are excellent, and time allows, a trial of a small dose of halogenated agent is sometimes done. If responses are poor without inhalational agents, ketamine may often be used to enhance the responses and allow a reduction in the propofol dosage.

The most challenging patients are those adults with neurological compromise and chronic pain where the patient is tolerant to anesthetic agents, especially the opioids. In these cases, adjunctive agents may play a key role. Hence ketamine or lidocaine is often used with SSEP and MEP, and dexmedetomidine used when MEP is not utilized. Since the most common problem with these patients is patient movement, rarely partial neuromuscular blockade is needed.

In general, the anesthesiologist should make the best possible choice of agents based on all the considerations and then work with the IOM team to identify if the anesthetic can be modified. In some circumstances, the addition of a low dose of inhalational agent may improve the ability to provide anesthesia while in others the addition of enhancing agents (e.g., ketamine) to lower or reduce depressant agents may be needed if possible. In any event, a stable constant anesthetic effect is desirable for the critical periods of the procedure so changes in IOM are not caused by changes in the anesthesia agents.

Challenges with Anesthesia

The primary challenges with the delivery of anesthesia rest in the four major anesthetic goals. Unfortunately, there are no accurate methods to titrate the infusions of sedatives, hypnotics, antinociceptive, and drugs used for immobility. Certainly, the occurrence of unexpected tachycardia or hypertension may indicate the effect of catecholamines released by noxious sensory stimulation. Similarly, patient movement may indicate inadequate blocking of the spinal reflexes in response to noxious stimuli. However, effective methods do not exist to determine the adequate doses of drugs to prevent these effects prior to an increase in sensory stimuli. As such clinical experience is often used and drug infusion doses may be more than needed (contributing to delayed awakening) or less than needed (leading to movement and hemodynamic changes).

Two IOM techniques can, however, provide some assistance. First is the observation of the background EMG activity. Since the muscles are normally quiet under anesthesia, EMG activity in multiple channels usually signifies inadequate anesthesia. Second, high frequency or high amplitude background EEG activity can assist in suggesting inadequate anesthesia. Unfortunately, there is no uniform effect of anesthetic effects on the EEG and the EEG only represents a cortical effect that does not always correlate with the drug effects on immobility at the spinal cord level (which often requires a higher dose than the dose for cortical effects). Fortunately, the dose of agents necessary for amnesia is usually below that which produces cortical effects in those drugs which produce amnesia.

Usually, burst suppression in the EEG is suggestive of adequate anesthesia but, as above the relationship is imperfect. Further, burst suppression is often intentionally produced as a means of lowering cerebral neuronal metabolism to about 50% of the awake state. Because the cortical neural structures are more sensitive to anesthetic effects, the SSEP can often be recorded despite the inability to use the EEG as a monitor of ischemia when burst suppression is present.

Commercial attempts at producing a processed EEG that represents the degree of drug effect

have led to devices to assist anesthesiologists. These might best be described as monitors of "depth of sedation" and many anesthesiologists find them helpful but not completely accurate in predicting adequate drug levels. Thus, during TIVA most anesthesiologists have concern that unexpected movement from inadequate blocking of the spinal reflexes. As such, the use of a small dose (e.g., ½ MAC) of an inhalational agent is often considered desirable when possible. This indicates that the IOM team can partner with the anesthesiologist to find a balance of anesthetic effects on IOM and a satisfactory anesthetic.

Conclusion

The anesthesiologist is clearly an important member of the team to facilitate IOM. Their knowledge of the patient and the pathophysiology of the medical comorbidities is essential to understand the neural physiology and the impact of surgery and procedure. The choice of anesthesia and management of the physiology is paramount for the success of the IOM. When IOM changes occur, their role is paramount since the etiology can usually be categorized as effects of anesthesia, physiology, positioning, technical, and of the procedure. As above, the anesthesiologist plays a key role in helping to identify the possible etiologies and assisting in improving the neural conditions to favor an improved outcome. This emphasizes the close working relationship between the IOM team, the anesthesiologist, and the surgeon or proceduralist.

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Somatosensory-Evoked Potential Monitoring

6

Marc R. Nuwer, Lara M. Schrader,
and Pedro Coutin-Churchman

Introduction

Somatosensory-evoked potentials (SEPs) are an excellent modality for spinal cord monitoring during surgery. They test much territory, including peripheral, spinal, brain stem, thalamic, and cortical levels of lemniscal sensory pathways. SEPs are used to monitor both spinal cord and cerebral injury during various types of surgery.

SEP intraoperative monitoring (IOM) is specific for the dorsal column-medial lemniscal (DCML) pathway but infers protection for other pathways as well. Stimulation of mixed peripheral nerves of the upper and/or lower extremity is accompanied by recording from various anatomic generators along the DCML pathway. The most common site for lower extremity stimulation is at the posterior tibial nerve (PTN) at the ankle. Alternate stimulation sites include the PTN in the popliteal fossa (behind the knee) or the common peroneal nerve at the knee. Recording sites include popliteal fossa, lumbar spine, a cervical site, and a cortical site from the scalp. For upper extremity SEP monitoring, the median or ulnar nerves at the wrist are most commonly stimulated with recording sites over the brachial plexus (at Erb's point), cervical spine, and scalp. Figure 6.1 shows an example of stable normal SEPs during a routine case.

SEP IOM is used to provide an alert to the surgeon about potential neurological complications. This is provided in real time so that an intervention could prevent an adverse outcome. SEP IOM also provides the surgeon with a reassurance that surgery is proceeding without complication. This reassurance gives the surgeon confidence to complete a procedure or to be more aggressive with correction, tumor removal, etc., thereby possibly making the surgery more successful. It is important that information (especially alerts) is given to the surgeon in real time. This allows correlation of the alert with surgical steps that may be undone in order to reverse the change.

Stimulation

SEPs are commonly used in the outpatient lab. In the operating room, the techniques are very similar. Table 6.1 summarizes the parameters used for intraoperative SEPs.

M. R. Nuwer (✉) · L. M. Schrader
UCLA School of Medicine, Department of Neurology, Los Angeles, CA, USA
e-mail: MRN@UCLA.edu

P. Coutin-Churchman
Ronald Reagan UCLA Medical Center, Department of Clinical Neurophysiology, Los Angeles, CA, USA

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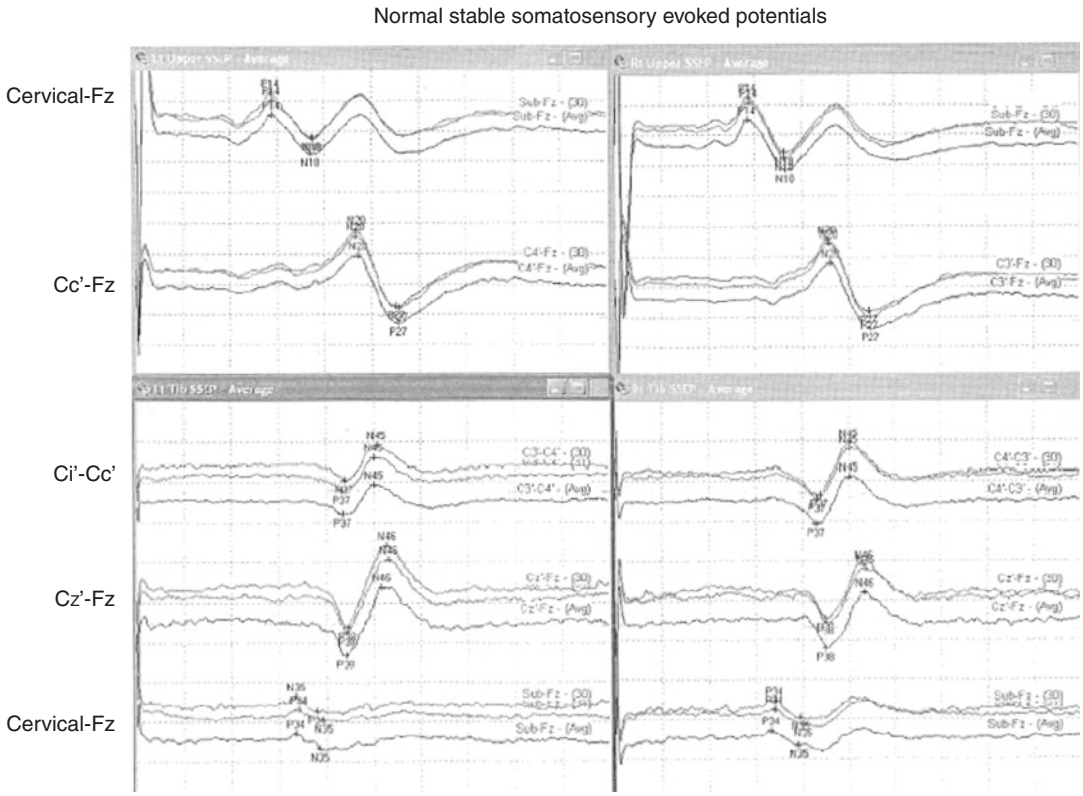

Fig. 6.1 Normal stable SEPs from the left and right median and left and right posterior tibial nerves. (From UCLA Department of Clinical Neurophysiology, with permission)

Sites

For the lower extremities, electrical stimulation to the *PTN* is applied to the ankle. That nerve is superficial and located just posterior to the medial malleolus. For some patients, the *peroneal nerve* is chosen instead. That nerve can be found superficially lateral to the knee, just below the fibular head. That site is useful especially in patients with a peripheral neuropathy, such as diabetics, and in the elderly. Upper extremity stimulation is delivered to the *median nerve* or *ulnar nerve*. Both nerves are superficial at the wrist.

Peripheral nerves may be stimulated unilaterally to test left- and right-sided pathways separately. For bilateral monitoring, left and right stimulation can be alternated during the same period of time in a method called asynchronous stimulation. Asynchronous stimulation allows for rapid data collection while still interpreting data with side-to-side specificity. Modern IOM equipment can average simultaneously from several sites using programmable protocols with delays between different stimulation sites.

Bilateral upper and lower SEP monitoring is used for some spine cases. Median or ulnar nerve stimulation is included in thoracic and lumbar cases as a means of monitoring for arm position or anesthesia-related changes. Ischemia secondary to hemodynamic events may also be detected by SEP monitoring from all extremities. Ulnar nerve monitoring also can help detect an incidental brachial plexus impairment resulting from patient positioning during long cases.

For cervical procedures, median or ulnar nerve pathways are the primary pathways

Table 6.1 SEP monitoring techniques

Stimulation
Lower extremity stimulation sites
Posterior tibial nerves at the ankle
Or peroneal nerves at the knee, e.g., in patients with peripheral neuropathy
Upper extremity stimulation sites
Median nerves at the wrist for intracranial cases and cervical cases C5 and above
Ulnar nerves at the wrist for spinal cases at or below C6
Stimulus intensity
Supramaximal (10% over intensity required to record maximal peripheral response)
Stimulus rate
5.1 per second per nerve, if tolerated with good peaks
Or slower if needed to obtain good peaks avoiding harmonics of 60
Recording
For lower extremity stimulations
Two cortical channels, CPi–CPc and CPz–Fpz
A cervical channel: CSp5–Fpz
For upper extremity stimulations
Two cortical channels, CPc–CPi and CPc–Fpz
A cervical channel: CSp5–Fpz
One peripheral channel: Erb's point ipsilateral, contralateral
Filters 30 and 3000 Hz, notch filter off, adjusting the filters as needed
300 trials per EP, more if needed

monitored. Because the ulnar nerves enter the spinal cord at a lower level, ulnar nerve monitoring is preferred for cervical cases at and below the C6 spinal level. PTN channels also are monitored in cervical cases for detection of a high thoracic or low cervical spinal cord injury. The four limb coverage also provides greater spinal cord protection from events such as hemodynamic changes.

Averaging

SEP data are low amplitude, often <1 μV. This amplitude is less than the surrounding background noise, which includes cerebral EEG activity. To find a reliable SEP measurement, data must be averaged. Averaging of low amplitude signals increases the signal-to-noise ratio (SNR) in a manner proportional to the square root of the number of trials. More trials result in better SNR. About 300 averaged recording trials often produce well-defined peaks.

Intensity

The correct way to determine the optimum stimulus intensity is to determine the intensity that produces the largest amplitude peripheral response and then add 10%. This is known as supramaximal stimulation and ensures that 100% of the nerve fibers are being recruited and that small changes in electrode resistance won't appreciably affect the recruitment percentage. Supramaximal stimulation will cause a 1–2 cm movement in the appropriate muscle groups in the absence of neuromuscular blockade. Median nerve stimuli produce thumb movement. Ulnar nerve stimuli produce fifth digit movement. PTN stimuli produce foot flexion, while peroneal nerve stimuli produce foot dorsiflexion. A stimulus artifact should be seen at time zero in recording channels, confirming that the stimulus is actually being delivered. Many modern IOM machines show current delivered and returned, and this also can be used to confirm stimulus delivery.

Electrodes

Stimulation electrodes can be needles, disks, or adhesive electrodes. An electrode pair consisting of a cathode and anode is secured over the nerve. The resistance between the electrodes and the skin should be <5 kΩ to ensure adequate stimulus delivery and avoid large stimulation artifact. Needle electrodes provide a low resistance and avoid resistance changes over long cases. For disk or adhesive electrodes, skin preparation with an abrasive is used to reduce electrical impedances. Patients allergic to citrus fruit may have a reaction to the skin preparation gel containing lemon. If using an

electrode paste, it should be free of calcium to avoid chemical burns from iontophoresis into the skin.

Rate

The repetition rate must strike a balance between rapid data collection and recording of a quality waveform. Typical repetition rates are between 2 and 5 stimulations per second. A complete data set can usually be obtained in a few minutes at these rates. Repetition rates >5 per second sacrifice data quality for more rapid collection. The amplitude of the peaks will decrease appreciably as rates increase above 5 pulses per second due to refractory times of the individual nerve fibers. Stimulation rates should avoid exact multiples of 60 Hz (or 50 Hz) to avoid line noise artifact.

Recording

Recording bioelectric signals involves optimization of several factors. At the beginning of a case, potentials should be optimized and set as baseline recordings suitable for comparing subsequent data during the procedure. Quality baseline recordings are essential to providing the surgeon with accurate data interpretation. Scouting for optimal baselines includes evaluating different recording sites, filter settings, and other parameters. A simple cookbook one-size-fits-all approach to SEP monitoring often leads to suboptimal recordings. The expertise of the monitoring team is in establishing the best recordings for each patient.

Recording Sites: General Comments

SEP recordings are made from successive sites along the DCML pathway. These recording sites are chosen to provide measurements from peripheral, spinal, subcortical, and cortical levels. In general, the active electrode is placed as near as possible to the anatomic generator, and a reference electrode is placed some distance away. The reference may be another scalp site or a non-cephalic site. Bipolar recording montages compare inputs between two nearby electrodes, while referential recording montages compare inputs between an active electrode near the anatomic generator and a much further placed reference electrode. The amount of electrical noise is proportional to the distance between the active and recording electrode as well as the distance between the anatomic generator and the active electrode. Cervical potentials are more susceptible to electrical noise because of the distance of the generator, yet these potentials are less affected by inhalation anesthetic concentrations due to the lack of synapses up to this point in the pathway. For this reason, they often are included in the recording montage despite their predisposition to noise.

The surgical field may make the preferred recording sites inaccessible. When this happens, it is necessary to scout for alternate recording sites that will yield the highest possible recordings. Neurosurgical craniotomies may displace scalp sites. Cervical surgery may displace cervical recording sites. Several nearby alternate sites may be tried.

Site Nomenclature

The International Federation of Clinical Neurophysiology's 10–20 System provides the accepted naming convention for scalp recording sites. The 10% extension of the 10–20 system [1] adds additional nomenclature. The EEG chapter in this book has further information on electrode nomenclature. For those unfamiliar with the naming conventions, a brief overview is given here. Electrode sites are named in a coordinate fashion with the first part of the binomial nomenclature indicating the anteroposterior position and the second part of the name indicating mediolateral position. A series of anteroposterior lines are named according to their position relative to certain brain features. The C-line runs generally along the central sulcus. The P-line is at the level of the parietal lobe. The line in between the C-line and P-line is the CP-line. Mediolateral positioning is named

relative to the lateral distance from the Z-line which runs along the vertex of the skull (midline). Odd numbers are to the left of the Z-line and even numbers to the right. The smaller the number, the closer to the Z-midline. For example, an electrode placed over the right postcentral gyrus near the hand area (lateral) would be CP4. The midline position would be named CPz. The location halfway between CPz and CP3 is known as C1. The letters "*i*" or "*c*" can replace the numbers when referring to general positions as either ipsilateral or contralateral, respectively.

Estimating recording sites by visual gross inspection, instead of measuring locations according to the 10–20 system, misplaces electrodes often by a centimeter or two. That misplacement may result in suboptimal recordings and poor ability to reproduce recordings if an electrode needs to be replaced after falling off.

SEP IOM also uses non-cephalic recording sites, e.g., over vertebral spines and at Erb's point. Erb's point is located above the clavicle, 2 cm lateral to the insertion of the sternocleidomastoid muscle. Sites over vertebrae are referred to by their spinal level, sometimes including the term Sp for *spine*. In that way, CSp5 is located over the fifth cervical spine's posterior spinous process.

Some recommended technical parameters are given in Table 6.1.

Lower Extremity SEP Recording Channels

Lower extremity SEP recordings are made from CSp5 and the scalp. The CSp5 channel monitors the cervical-brain stem activity, and the scalp channels monitor cortically generated peaks.

There is no single correct scalp recording site for the cortically generated peak of the lower extremity SEP. The cortical generator's dipole is oriented differently in different patients and can change with the depth of anesthesia. Principal sites for the active electrode include CP1, CP2, CP3, CP4, and CPz. The orientation of the neurons that generate the potential changes as the postcentral gyrus bends toward the midline. The orientation of the midline neurons that generate the cortical potential in response to lower extremity stimulation causes the dipole to project across the midline. This dipole projection results in a "paradoxical localization" of the potential over the scalp ipsilateral to limb stimulated. This is paradoxical in that the neurons generating the potential are located in the contralateral hemisphere (as indicated by DCML pathway anatomy). Common sites for the active electrode are CPi, CPc, and CPz.

Choosing a site for the reference electrode is also important. Scouting possible recording channels early in the case helps to find the best channels to monitor in that patient, although time may not permit this exercise. References may include the forehead, ear, mastoid, or the scalp location contralateral to the active electrode. Short distances between the active and reference electrodes (e.g., CPi–CPc) reduce noise but also may reduce peak amplitudes.

The subcortical peaks may be recorded over the spinous process of C5 (CSp5) with an ear, forehead, or contralateral shoulder as a reference. The subcortical peaks are less affected by anesthesia due to the lack of synapses at this point of the DCML pathway. Peripheral recording sites include the popliteal fossa or over the lumbar and thoracic vertebrae such as TSp12 or LSp1. Older and obese patients may have no recordable lumbar potentials as a normal variant.

Upper Extremity SEP Recording Channels

For upper extremity SEPs, recordings are made at the shoulder, cervical spine, and scalp. Scalp sites are generally optimum over the contralateral postcentral gyrus (CPc) with a forehead, ear, or mastoid reference. Subcortical peaks popularly are recorded from CSp5, earlobe, or mastoid with a reference located either at the forehead or contralateral Erb's point. An Erb's point channel (referenced to the contralateral Erb's point) can be used to test peripheral conduction and is useful for monitoring changes secondary to positional issues.

Filters

The typical low-frequency filter is set to 30 Hz and high-frequency filter 500–1500 Hz. This balances control over noise while maintaining most SEP peak characteristics. These settings reduce random amplitude fluctuations and some anesthetic-related variability [2]. Properly set filters will yield reproducible SEPs with minimum background variability in amplitude and latency.

Notch filters should not be used during SEP recording. The notch filter can cause a stimulus artifact with a decaying sinusoidal tail with peaks at 16.6, 33.3, and 50 ms. Those peaks easily can be mistaken for stable EPs at 16.6 or at 33.3 ms. This is called a ringing artifact.

Digital smoothing filters are available on most modern IOM equipment. They can distort the peak, possibly mixing artifact with a peak in ways that make interpretation more difficult. Excessive smoothing is to be avoided.

It is always recommended to eliminate background and environmental noise at its cause when possible, instead of masking the noise with filters. Scouting is undertaken to find channels less affected by noise. Sometimes changes can be made to filter settings, but with care to avoid the negative effects of such changes. These effects include changing the signal morphology as well as introducing a phase shift.

Primary Peaks

Lower Extremity SEPs

The P37 is the primary cortical peak generated by the somatosensory cortex. Often it is seen on the scalp ipsilateral to the leg stimulated at 37–45 ms after PTN stimulation at the ankle in normal patients. It is longer in taller individuals, the elderly, or those with pathology. The P37 generator lies in the vascular territory of the anterior cerebral artery. Figure 6.2 shows the lower extremity SEP peaks and nomenclature in a typical case.

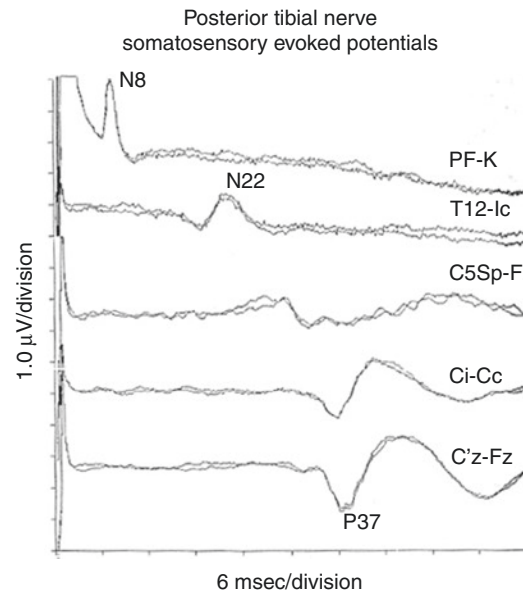

Fig. 6.2 Somatosensory-evoked potentials from posterior tibial nerve stimulation are shown. Typical peaks N8, N22, and P37 are noted. A cervical peak was also found. These peaks have normal latencies and amplitudes. (*PK* popliteal fossa, *K* knee, *T12* T12 spine, *Ic* contralateral iliac crest, *C5Sp* C5 spine. Reprinted with permission from Nuwer et al. [4])

The cervical peak is a far-field signal seen around 31 ms after stimulating the PTN at the ankle. The likely generator of this (N31) peak is the nucleus gracilis at the cervicomedullary junction. A trough following the cervical peak may represent conduction along the medial lemniscus or a thalamic potential. Amplitude and latency measurements for the cervical peaks are used especially when the cortical P37 is poorly suited for monitoring. Anesthetic has much less effect on the cervical peaks due to the absence of synapses from the point of stimulation, so the cervical peak is more stable when anesthesia effects are prominent. These subcortical potentials lie in the vascular territory of the vertebra-basilar complex.

The N22 peak is a negative potential around the T12 spine at approximately 22 ms after

stimulation. It is generated in the lumbar spinal cord, i.e., anatomically around the T12 spine. It represents the culmination of the peripheral pathway conduction up to and into the lumbar spinal cord. Peripheral peaks are monitored to clarify that decreased cortical potentials are due to a surgical problem rather than a problem with the stimulus or a positional issue. The popliteal N8 peak also could be used in a similar way.

Upper Extremity Peaks

The N20 is the cortically generated peak for upper extremity SEP IOM. The peak's amplitude and latency are measured, and used as criteria to monitor neurologic function. The peak arises from the primary somatosensory cortex on the postcentral gyrus contralateral to the side of stimulation. It is best seen recorded from an active electrode at CPc. The N20 lies in the vascular territory of the middle cerebral artery.

The subcortical peak is recorded with the same montage used for recording lower extremity subcortical potentials. The N13 cervical spinal cord peak arises from the mid-cervical spinal cord at the C5 level where the median nerve roots enter the spinal cord. For ulnar nerve stimulation, the peak arises from the sixth or seventh cervical spinal cord. This N13 peak is followed by a positive P14 peak generated by the nucleus cuneatus and its decusation of the medial lemniscus. Rostal to those peaks, an N18 arises from the thalamus. The N18 is often obscured by its proximity to the N20. For this reason, a CPi–EPc recording channel can be used to isolate the N18. These subcortical N13 and P14 potentials are in the vascular territory of the vertebra-basilar complex, and the N18 posterior communicating artery territory.

A peripheral N9 peak is recorded over the brachial plexus at Erb's point. The blood supply for this potential is the axillary artery. Figure 6.3 illustrates typical upper extremity SEP peaks and their nomenclature.

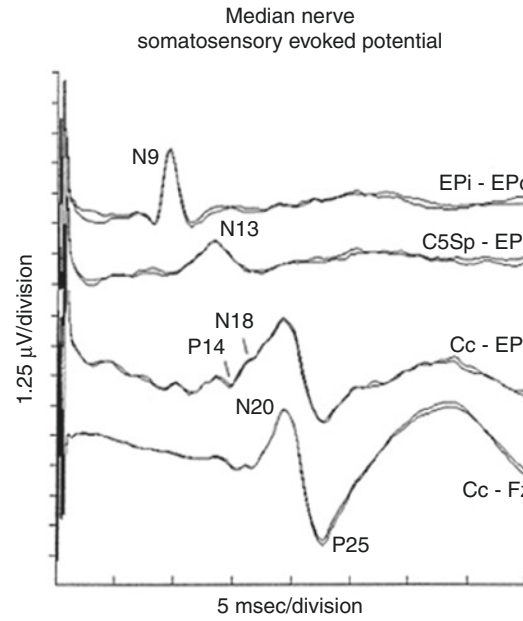

Fig. 6.3 Somatosensory-evoked potentials from median nerve stimulation are shown. Typical peaks are shown in each of four recording channels. The test is normal. (*EPi EPc* Erb's point ipsilateral, contralateral. Reprinted with permission from Nuwer et al. [4])

Interpreting Change

Characteristics of the SEP waveform including latency, amplitude, and area under the curve. These are useful to interpret changes from baseline. In order for any test to be useful for the purposes of IOM, it should have an adequately high sensitivity and specificity. When changes in latency and amplitude are used for SEP IOM, this test is nearly 100% sensitive and specific. This means that there are very few false positives or negatives with SEP monitoring. Typical alarm criteria for SEP IOM is a 50% decrease in amplitude and/or a 10% increase in latency [3, 4]. For very stable peaks, a criterion of 30% to 40% decrease may be used. When these thresholds are crossed, the monitoring team quickly assesses the reason for the change. Technical issues should be quickly resolved. Changes due to anesthesia should be documented and communicated with the surgical team and anesthesiologist. Surgical-

induced changes should be immediately reported to the surgeon as they may warrant intervention.

Anesthetic effects are one of the main reasons for an SEP IOM change. Inhalntion anesthetics, nitrous oxide, or bolus injections may reduce the amplitude of the SEP signal. Since anesthetic works primarily at synapses, cortical potentials are most susceptible to anesthetic effects, while subcortical and peripheral potentials remain relatively stable. *Anesthetic fade* refers to a gradual reduction in amplitudes during the first 30 min after induction and to a smaller extent over subsequent hours of a long case. Anesthetic fade is most common with inhalation anesthetics.

Preexisting impairment may magnify anesthesia effects (Fig. 6.4).

Technical problems should be ruled out when signals change. When a technical issue is suspected, it is important to distinguish between a stimulation and recording issue. Large increases in electrode impedance suggest a recording problem such as a dislodged electrode. Absence of a stimulation artifact or poor current return indicates that there is a problem with stimulus delivery. Another common recording problem is the introduction of electrical noise. In this case, the live (unaveraged) waveform should be viewed and the frequency band of the noise be identified. The first priority should be to find and eliminate the source of the noise. If that fails, changing the passband by adjusting filter settings may be required.

Perisurgical factors may also induce SEP data changes including hypothermia, hypotension, and hypoxia. Cooling can increase latencies. Cooling can be systemic, in a limb, or because of local irrigation. Substantial cooling can cause SEP cortical peak amplitude loss, even decreased to isoelectric

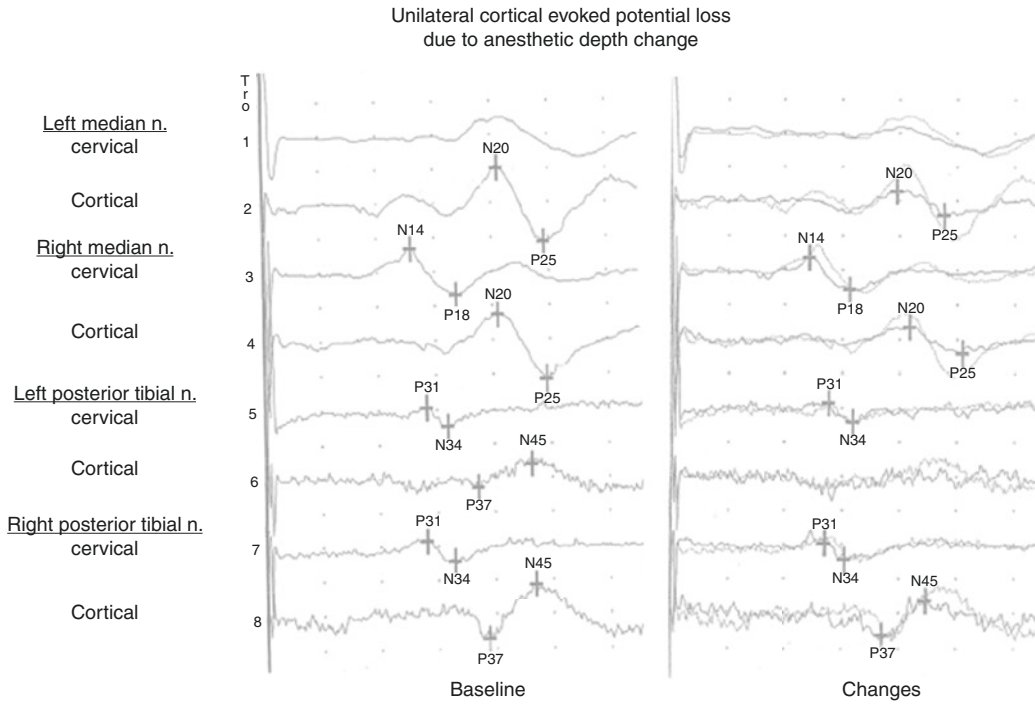

Fig. 6.4 The baseline testing shows a relatively attenuated left lower extremity cortical peak (*left* tracings). After an increase in anesthetic depth (*right* tracings), that channel no longer shows a reliable SEP (The baseline is superimposed on the newly acquired tracings at the *right*.) An anesthetic effect is the likely cause of the change, as suggested by both the preserved subcortical peaks for the affected pathway and somewhat attenuated cortical peaks in all other pathways. (From UCLA Department of Clinical Neurophysiology, with permission)

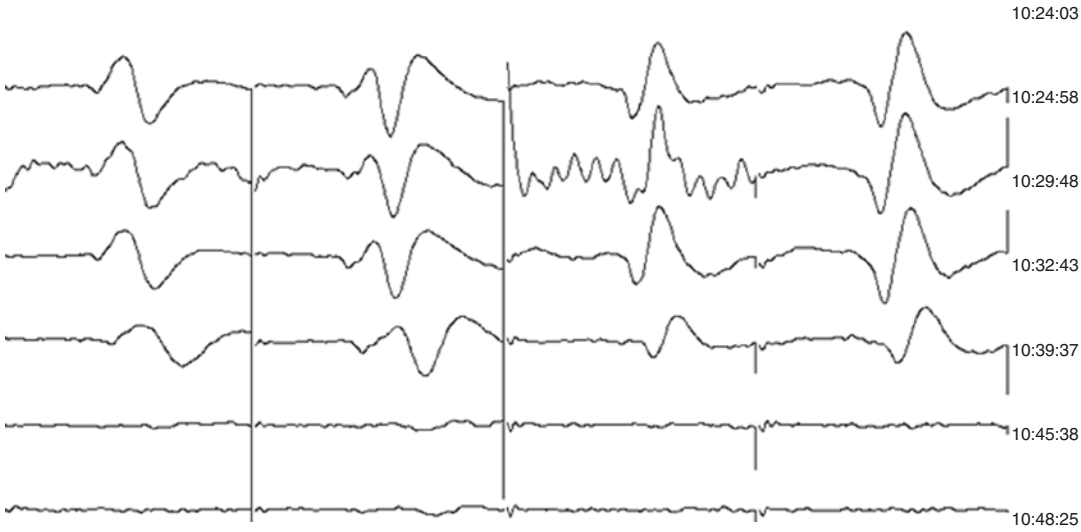

Fig. 6.5 Temperature effects on SEPs. Left and right median and left and right posterior tibial nerve SEPs are shown over 25 min as the patient's core temperature dropped from 34 to 20 °C. Time flows from top to bottom. Latencies increase, amplitudes decrease, and then the peak essentially disappears

recordings at temperatures below 22 °C (Fig. 6.5). Preexisting spinal cord compression may leave a patient especially sensitive to hypotension due to autonomic dystonia. Correlation of SEP changes with the anesthesia doses, the patient's temperature, and blood pressure will help determine the cause of change and a solution. It should be mentioned that just because a change is not deemed surgical does not make it clinically insignificant. A change resulting from hypotension indicates that the brain is not being adequately perfused. It is necessary to communicate this to the surgeon and anesthesiologist so that corrective action may be taken.

Surgical problems also cause changes, which is likely the reason you were asked to monitor the case to begin with. Types of surgical issues that can cause data changes include direct blunt trauma, excessive retraction or compression, stretching of structures, vascular insufficiency, vasospasm, embolus, thrombus, or other clinical problems. Not all amplitude decreases are clinically significant, meaning not all will result in a deficit. The likelihood that an amplitude reduction predicts an adverse outcome increases as the amplitude decrease worsens and the longer the change persists. Early identification of changes leading to prompt intervention is critical to preserving function. A 50–80% transient amplitude decrease for only a few minutes poses a small-to-modest risk of postoperative neurologic deficits, especially if the SEPs return promptly to baseline values following intervention. Higher risk is incurred with abrupt changes, complete loss, and persistent attenuation. The gravest situation is the abrupt, persistent, complete loss of previously easily detected SEPs. Even an abrupt persistent loss does not always predict impairment. The risk in that case is about 50–75% [4]—a deficit is not a foregone conclusion.

Stable intraoperative SEPs are highly predictive of a good neurological outcome. A patient will have a neurologic injury despite the preservation of intraoperative SEPs in fewer than 0.1% of cases (Table 6.2). This degree of sensitivity and specificity makes SEPs the gold standard for intraoperative spinal cord monitoring. IOM-prompted surgical interventions are successful at reducing postoperative neurological deficits. The use of IOM reduces paraplegia by 60% for spinal surgery [4].

Table 6.2 Neurologic outcome prediction rates for SEP monitoring in spinal surgery

False-negative rate	
Neurologic postoperative deficits despite stable SEPs	
Definite	0.06%
Total	0.13%
False-positive rate	
No neurologic deficits despite SEP changes	
Definite	0.98%
Total	1.51%
True-positive rate	
Neurologic deficits predicted by SEP changes	
Definite	0.29%
Total	0.42%
Neurologic deficits	
False negative plus true positive	
Definite	0.36%
Total	0.55%
Sensitivity	92%
Specificity	98.9%
Positive predictive value	42%
Negative predictive value	99.93%

These data are from a large multicenter US outcome study of SEP spinal cord monitoring organized through the Scoliosis Research Society. Note the rate of definite false-negative cases is low (0.06%). The very high negative predictive value here indicates the high reliability of the monitoring when the SEP remains normal and stable. The outcome survey report [5] discusses in detail these data and related assumptions

Finding the Motor Cortex

In addition to monitoring, SEPs can be used to test for the location of motor cortex. The median nerve SEP stimulation technique is used. Recording is from a 1 by 8 strip of cortical electrodes laid directly onto the exposed cerebral cortex. A nearby reference electrode is placed at a neutral site such as on dura or muscle. The N20 peak appears at the primary somatosensory cortex on the posterior edge of the central fissure. By determining the N20 location, one can deduce that the next more anterior gyrus is the motor cortex. The strip electrode may be moved several times to find the thumb level of sensory cortex that corresponds to the median nerve stimulation site.

Clinical Indications

There are many indications for the use of SEPs in the operating room [6]. The most common use is for spinal cord monitoring in cases involving scoliosis, cervical myelopathy, fractures, tumors, and other disorders that put the spinal cord at risk during surgery. SEPs also are used to monitor the intracranial portions of the somatosensory pathways. For example, SEPs are useful for monitoring the brain stem during surgeries to remove cerebellopontine angle tumors, during cranial nerve microvascular decompression procedures, brainstem and cerebellar tumor resections, aneurysm clippings or coilings, and decompression of Chiari malformations. SEPs are used to monitor the internal capsule and cerebral cortex for ischemia during carotid endarterectomy, brain tumor removal, arterial-venous malformation resection, aneurysm clipping, epilepsy surgery, and other procedures placing the cerebral cortex at risk.

In each case, similar SEP parameters and criteria for change are used. The nerve chosen for stimulation may differ based on the objective of the procedure. Median and posterior tibial nerve SEPs are monitored most often. The peroneal nerve at the knee may be substituted for the posterior tibial if the patient has a peripheral neuropathy or has an amputation below the knee. The ulnar nerve is used in place of the median in spine surgery at or below C6 to give better coverage of the whole cervical spine. The ulnar nerve is also most vulnerable to arm positional injury, so monitoring is indicated for the ulnar nerve SEPs during thoracic or lumbar cases.

For intracranial cases, the choice of SEP monitoring should depend on the vascular territory at risk. Lower extremity SEPs are important to monitor for cases involving risk to the vascular territory of the anterior cerebral artery. Upper SSEPs monitor the territory of the middle cerebral artery. For intracranial cases, the recording

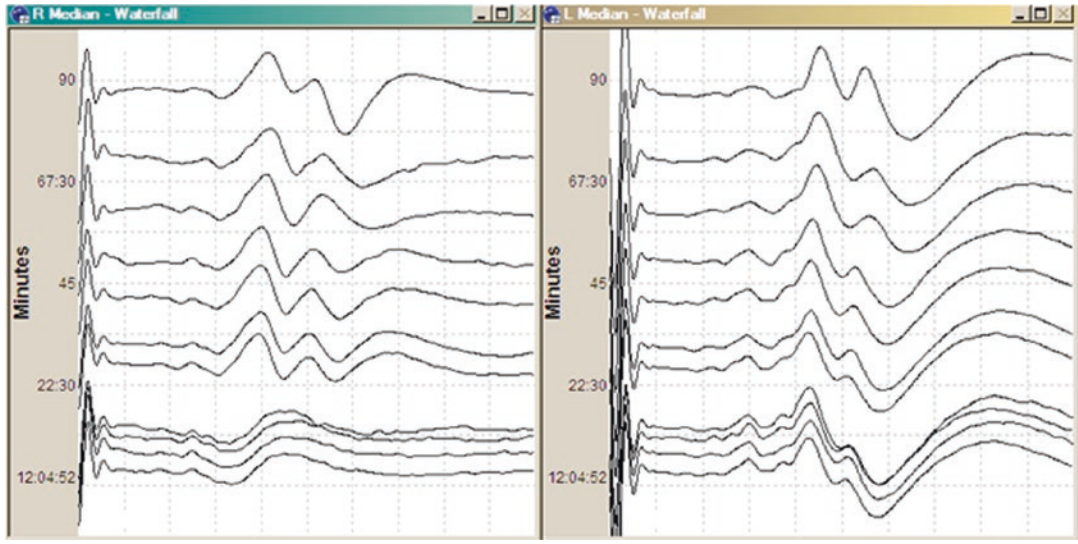

Fig. 6.6 A 68-year-old woman during left internal carotid artery aneurysm clipping after a subarachnoid hemorrhage complicated by arterial dissection. During surgery, the right median (shown) and posterior tibial (not shown) SEPs' cortical peaks for the left hemisphere were lost within 20 min of clipping, at a time when further aneurysmal bleeding was encountered. Time reads from the top downward (later tracings at the *bottom*). Ninety minutes of the monitoring is shown around the time of clipping. Note how the N20 peak is replaced by a lower amplitude far-field potential generated at the thalamic or high brain stem level, so the tracing is not flat. At the same time, the contralateral side remains stable. This patient suffered a thrombosis in the middle cerebral artery territory ischemic infarct despite the SEP alarm

electrodes may need to be moved away from the craniotomy flap. Figure 6.6 shows an example of an SEP recorded from alternate scalp locations during an aneurysm clipping.

If SEP IOM is being used to protect a peripheral nerve, such as the sciatic, then the anatomy will dictate the proper stimulation sites. For example, when monitoring sciatic nerve, the peroneal portion that is most at risk during hip replacement surgery. In the case in which the sciatic nerve is at risk, it may be appropriate to monitor both the posterior tibial and peroneal nerves.

SEP IOM remains the modality best supported in the literature. In a formal assessment process, the American Academy of Neurology and the American Clinical Neurophysiology Society jointly concluded and recommended that IOM is established as an effective means to predict an increased risk of the adverse outcomes of paraparesis, paraplegia, and quadriplegia in spinal surgery based upon four Class I and seven Class II studies. Surgeons and other members of the operating team should be alerted to the increased risk of severe adverse neurologic outcomes in patients with important IOM changes [7]. A large multicenter study of spinal cord SEP monitoring showed a 60% decrease in paraplegia and paraparesis associated with monitoring [4]. Validity measures and neurologic deficit rates from that study are shown in Table 6.2.

Sala et al. [8] studied motor outcomes for intramedullary spinal cord tumor surgery. Historical controls were used from the time prior to the adoption of IOM. If IOM showed changes, myelotomy was moved to a different location along the tumor or temporarily stopped. Sala

measured the McCormick grade of weakness for patients with EP monitoring, and compared those results to patients without EP monitoring. For the patients with IOM, the preoperative to postoperative change in McCormick grade of weakness was +0.28. For the patients without IOM, the preoperative to postoperative change was −0.16. The difference between groups was significant ($p < 0.002$).

Many animal studies also support the validity of IOM. They show that raising an alarm at a suitable point in time gives the surgeon enough time to intervene and avert a postoperative neurological deficit in many patients. For that reason, IOM SEP is considered clinically useful by most and should be used when there is a reasonable risk of neurological injury from surgery.

Questions and Answers

1. The best tradeoff for SEP stimulation rate for a teenager is often around.
   (a) 3 per second
   (b) 5 per second
   (c) 7 per second
   (d) 9 per second
2. When cortical SEPs are low amplitude, tactics to improve the signals' amplitude include
   (a) Faster stimulation rates
   (b) Lower low filter setting
   (c) A smaller sample size to produce EPs more quickly
   (d) Turning on the notch filter
3. In the 10–10 system, electrode site CP2 is located
   (a) Halfway between Cz and P4
   (b) Halfway between Cz and C4
   (c) Halfway between Pz and P4
   (d) Halfway between C4 and P4
4. The peripheral recording site Erb's point is at
   (a) 5 cm above the mid-clavicle just lateral to the sternocleidomastoid
   (b) 2 cm above the mid-clavicle just lateral to the sternocleidomastoid
   (c) Above the clavicle, 2 cm lateral to the insertion of the sternocleidomastoid
   (d) Above the clavicle, 5 cm lateral to the insertion of the sternocleidomastoid
5. The most likely location for the best amplitude of the P37 peak for right posterior tibial SEP testing is
   (a) C1'
   (b) C2'
   (c) Cz'
   (d) CPz
6. Recording site PF is at
   (a) Posterior frontal
   (b) Popliteal fossa
   (c) Parietofrontal
   (d) Parafrontal
7. The most commonly used criterion for alerting a drop in posterior tibial SEPs is:
   (a) 10% amplitude loss or 2 ms latency increase
   (b) 30% amplitude loss or 3 ms latency increase
   (c) 50% amplitude loss or 4 ms latency increase
   (d) 70% amplitude loss or 6 ms latency increase
8. The greatest amplitude decreases in cortical SEPs are commonly associated with.
   (a) Too high a setting of the stimulus intensity
   (b) Cooling to 32 °C
   (c) MAC use of inhalation anesthetics
   (d) Too low of a low filter setting

Answers

1. (b)
2. (b)
3. (a)
4. (c)
5. (b)
6. (b)
7. (c)
8. (c)

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Motor Evoked Potentials

7

Jay L. Shils and Vedran Deletis

Introduction

Iatrogenic injuries are an undesired consequence of surgery, yet iatrogenic injuries to the motor system are much more devastating to a patient's quality of life than most injuries to the sensory system. In many cases, intraoperative injuries to the spinal cord will be detected by sensory evoked potentials (SSEPs), yet a focal injury to the anterior spinal artery (ASA) may be missed [1]. There is a lot of evidence in the literature describing selective injury to the anterolateral columns sparing dorsal columns with preserved SSEPs [2–5]. The inclusions of motor evoked potentials (MEPs) to the intraoperative monitoring *toolbox* can help to confirm/prevent selective lesions to the anterolateral columns of the spinal cord. Additionally, MEPs, compared to SSEPs, can more quickly detect an ischemic injury to the spinal cord [6]. Yet, MEPs are not without their limitations. Even given these limitations, proper application and interpretation of MEP data can be a significant adjunct in reducing iatrogenic injury during surgery.

History

Artificial stimulation of the motor system dates to 1664 when Swammerdam removed the heart of a frog and demonstrated that by gently stroking the severed nerve ends of the open wound the muscles would contract [7]. The most well-known experiment comes from Luigi Galvani when in 1771 he observed that electrical sparks applied to the nerves in the leg of a frog would cause twitches in the leg muscles [8]. In the 1860s, Hitzig and Fritsch stimulated the exposed brains of soldiers using direct cortical stimulation (DCS) and found that they could cause *crude* movements [9]. They continued their work on live dogs and found that not only could they cause these *crude* movements, but they also observed that specific areas, when stimulated, caused specific movements [10]. In the late 1930s, the neurosurgeon Wilder Penfield published his mapping studies of the human brain performed during epilepsy and tumor resection surgeries [11]. Penfield not only localized the motor and sensory areas of the brain but also defined the cortical somatotopy or motor and sensory homunculi of these two cortical areas. Penfield's basic stimulation technique, 60 Hz

J. L. Shils (✉)
Rush University Medical Center, Chicago, IL, USA

Rush University, Department of Anesthesiology, Chicago, IL, USA
e-mail: jay_l_shils@rush.edu

V. Deletis
Department of Neurosurgery, University Hospital Dubrava, Zagreb, Croatia

Albert Einstein College of Medicine, New York, NY, USA

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trains of stimuli lasting for one to a few seconds, is still practiced for cortical mapping of language and sensory areas. In the 1950s, Patton and Amassian were the first to record direct traveling waves from corticospinal tracts (CST) when stimulating the motor cortex/subcortex in both cats and primates [12]. They observed two types of waves: the first was a short-latency triphasic response termed the D-wave (direct wave), interpreted as a result of the direct activation of the CSTt, and the second set of waves were termed I-waves (indirect waves), interpreted as trans-synaptic activation of motor neurons of the CST within the motor cortex [13].

Research on the motor system continued, yet there existed no direct method to deliver stimuli to a subject's brain without accessing the brain directly given the extremely high impedance of the skull. In order to electrically cross this high impedance barrier, high stimulus currents are needed to activate the underlying neural tissue. In 1980, Merton and Morton developed a high-voltage single-pulse technique for the delivery of transcranial electrical stimulation (TES) to the intact human subject [14] (it should be noted that they discuss that this stimulation was "without undue discomfort" to the subjects).

One interesting study using this method was published after the work of Merton and Morton, by Levy et al., that delivered TES via an anodal electrode placed over the motor cortex and a cathodal electrode placed on the hard palate to record D-waves, via either electrodes placed over the thoracic spinal canal or by inserting electrodes into the level of the bony laminae or directly in the epidural space during surgery [15]. They claimed that these recordings represented descending activity of the motor system. In addition to demonstrating the recording, Levy et al. discuss using multiple pulses to help produce motor activation at lower stimulation levels, yet this idea was not pursued [15] until much later as will be seen below. In the late 1980s, Katayama and Tsubokawa recorded D-waves from the epidural space of the spinal cord stimulating surgically exposed motor cortex [16]. Epidural spinal electrodes were inserted percutaneously into the upper thoracic epidural space under X-ray control and pushed cranially to the lower cervical epidural space. During surgery the motor cortex and other cortical areas were then directly stimulated using both monopolar and bipolar stimulation. They demonstrated that direct application of monopolar anodal current to the motor cortex required lower stimulation intensities as compared to cathodal bipolar stimulation [16]. In order to better refine the most optimal stimulation configuration and also to understand the phenomena of latency changes with increasing stimulation current, Burke et al. proposed the discrete jumps in latency to be due to bends in the CST as the stimulation moved deeper in the brain [17]. A set of papers by Deletis, Rodi, and Amassian described the neurophysiologic mechanism underlying MEPs in anesthetized humans which is of importance in understanding the pitfalls during the routine use of MEP monitoring in the operating room [18, 19].

Physiological Background for Monitoring the Motor System

Depending on the type, location, and intensity of stimulation, the MEPs recorded during intraoperative neuromonitoring (IONM) are generated and transmitted from a limited subset of neural elements. These responses are, for the most part, transmitted by the largest fibers of the CST, and in deeply anesthetized patients, this electrical stimulus activates these largest fibers directly. It is important to note that it is the axons that are being activated and not the cell bodies. Additionally, as the stimulus intensity increases, the depth of stimulation also increases. The exception is in the awake subjects/patients or use of transcranial magnetic stimulation (TMS) where the pyramidal cell body is activated by interneurons ending up on the pyramidal cells in the cortical gray matter. Yet even given that we are testing a limited subset of the motor system, the data obtained with this method can still be useful for patient protection, and the physiology behind these responses needs to be properly understood in order to make proper data interpretations in the operating room.

Anatomy and Physiology of the Motor System

The motor system is a complex combination of neural subsystems existing in both the central and peripheral parts of the nervous system. It is important to realize that artificial stimulation most likely activates many different cortical fibers, while MEP monitoring techniques only record responses from a small portion of them (Fig. 7.1). The primary anatomic structures activated by transcranial MEPs (TcMEPs) are the axons of the Betz cell in layer 5 of the motor cortex. These axons are part of the CST and corticobulbar tract (CBT) which are upper motor neurons. These axons decussate at the level of the medulla and travel down the spinal cord to the α-motor neuron (αMN) whose cell body is located in the ventral gray of the spinal cord. The (αMN) is the lower motor neuron. Upon synapsing on the αMN, its axon travels out through the ventral root of the spinal cord to the peripheral nerves

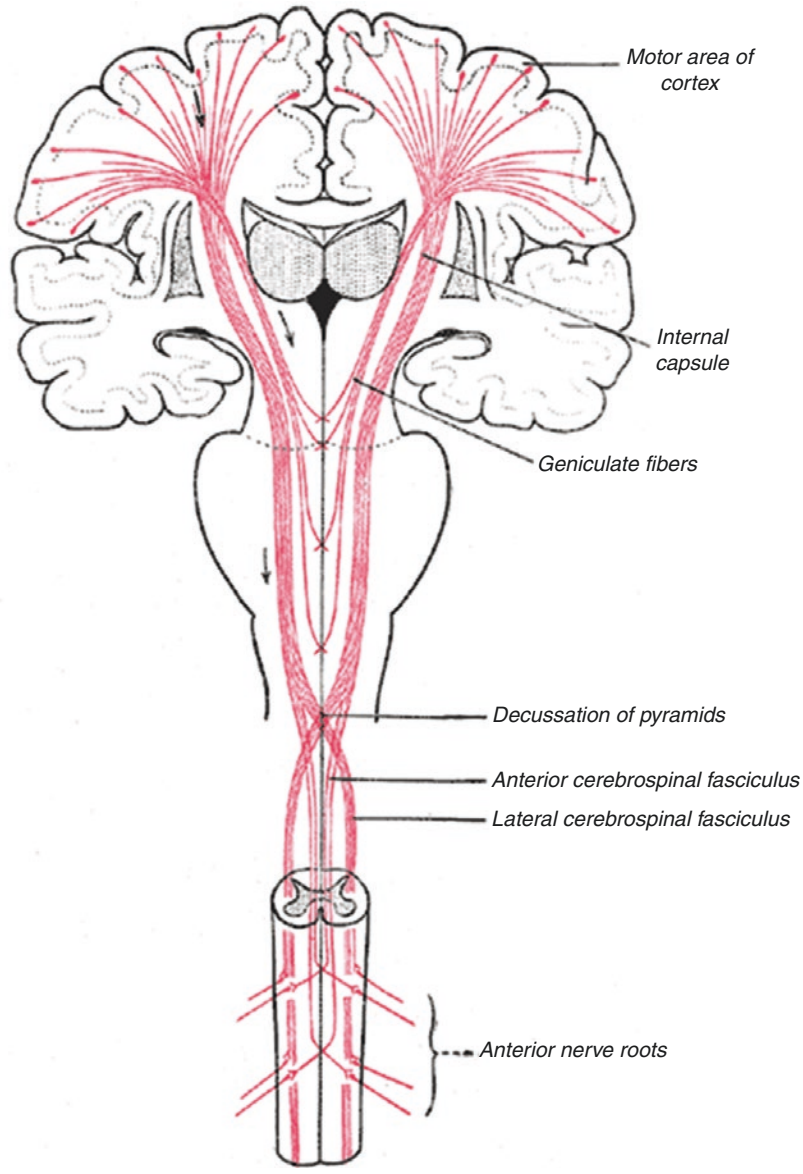

Fig. 7.1 Multiple areas of the cortex are involved in motor movements. In addition to the cortex, there also exist multiple subcortical areas. During artificial simulation under anesthetics, the corticospinal fibers are the main carriers of that stimulation information to the alpha motor neurons in the spine. Even though the stimulation will activate fibers from other areas, this information is usually not passed due to the synaptic junctions between the other areas and the corticospinal tract which under anesthesia are shut down for the most part. (From http://thebrain.mcgill.ca/flash/a/a_06/a_06_cr/a_06_cr_mou/a_06_cr_mou.html (copy left) and with permission from the GNU free documentation license)

and then finally to the muscle. The primary motor cortex, where the CST fibers originate, is located in the precentral gyrus and is primarily responsible for fine voluntary movement. This area of the cortex receives information from multiple cortical areas which include the extrapyramidal systems (areas such as the basal ganglia and cerebellum) and sensory areas including somatosensory, visual, auditory, both parietal, and frontal cortices. The primary motor cortex has a map of the body, or homunculus, with the head located laterally on the cortex and the leg located centrally. This topography illustrates the cortical surface area dedicated to innervation of parts of the body. See Chap. 2 for more information on the homunculus. The corticospinal and corticobulbar pathways are shown in Fig. 7.2.

At the surface of the cortex are six layers of gray matter. Each functional area of the brain has different proportions of each of these six layers, yet the basic six-layer structure is the same throughout the cortex. Each area of the cortex is defined based on its specific cytoarchitecture and neural organization. The nomenclature used for this differentiation is known as a Brodmann area [20]. Interestingly each Brodmann area generally corresponds to a specific functional area, even though the original differentiation was purely based on its cytoarchitecture (http://www.fmriconsulting.com/brodmann/Introduction.html). Generally layer 5 is the output while layer 4 is the input layer. The primary motor area (PMA), or Brodmann area 4, is located in the posterior portion of the frontal lobe just anterior to the central sulcus (Fig. 7.3). Layer 5 of the primary motor cortex contains large pyramidal cells known as Betz cells that send long axons directly to motor neurons located in the spinal cord or brainstem via the CST or CBT (the combination of these two tracts is known as the pyramidal tract). About 60% of the human CST arises from the primary motor cortex and area 6 (premotor area and supplementary motor area); the other 40% arises from the somatosensory cortex (areas 1, 2, and 3) and cingulate cortex (areas 23 and 24) [21, 22]. Even though all areas of the body are represented within the primary motor cortex, it appears that more proximal and axial muscle fibers in the CST have their origins in the premotor area (area 6), while the distal musculature tends to have its origin in the premotor areas (area 4) [23]. Since both sets of fibers are contained in the CST, stimulation used during IOM will activate both of them. From the cortex the CST funnels into the anterior half of the posterior limb of the internal capsule and then travels between the thalamus and parts of the basal ganglia (striatum and globus pallidus) to the ventral portion of the cerebral peduncles (in the middle two-fifths of the cerebral crus—anterior portion of the cerebral peduncles). At this level, the fibers that will eventually synapse on αMNs in the spinal cord gray matter innervate leg muscles and are lateral to fibers eventually innervating hand muscles. From the midbrain, the CST fibers enter the pons and pass through the pontine nuclei where fibers going to the leg muscles are now located ventrolateral relative to the fibers going to the hand muscles. The CST enters the ventral part of the medulla forming part of the medullary pyramids where fibers innervating the lower limbs are located ventrolateral compared to the fibers innervating the upper limbs. At the lower level of the medulla, 80–90% of the CT

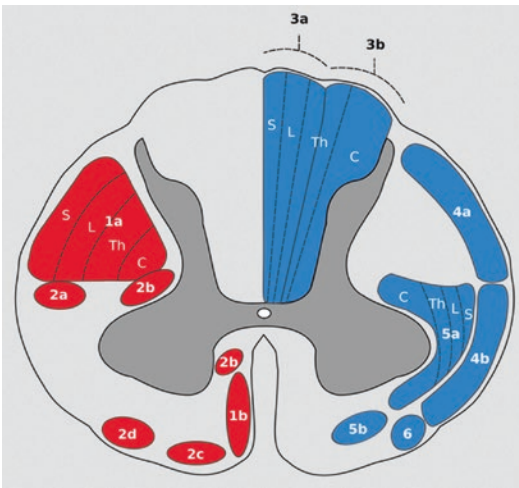

Fig. 7.2 The lateral corticospinal tract (1a in the figure) shows a lateral to medial homunculus with the sacral region being most lateral and the cervical region being the most medial. Region 1b is the anterior corticospinal tract in the spinal cord. (With permission from Wikimedia Commons—public domain)

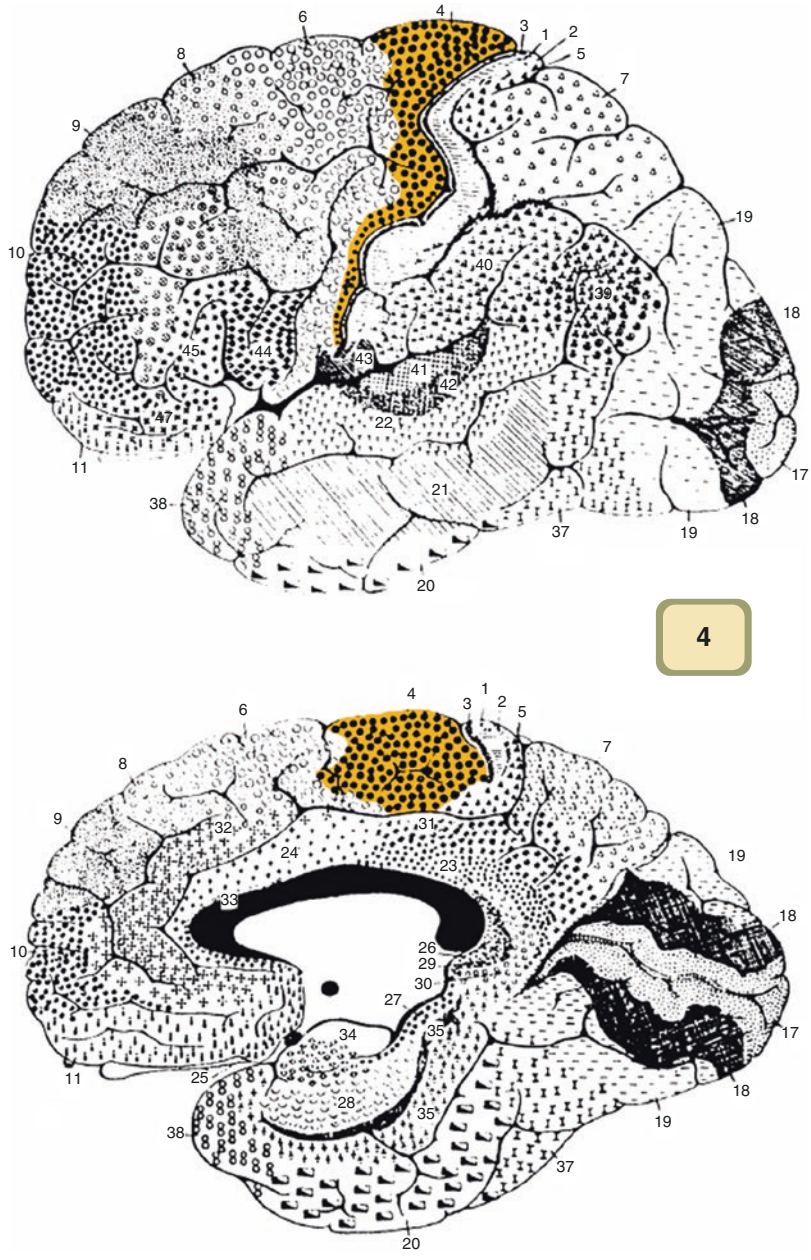

Fig. 7.3 Map of the cortex with all of Brodmann areas depicted. Area 4, the primary motor cortex, is *highlighted*. Area 4 is just anterior to the central sulcus. (With permission from Wikimedia Commons—public domain)

decussates with most fibers entering lateral CST of the spinal cord. Fibers going to the lower limb muscles tend to cross more rostrally than for the upper limbs. The 10–20% of uncrossed fibers in the anterior CST innervate αMN ending on more proximal and trunk musculature [24].

There are about one million fibers in each CST with around 2% of these fibers being large (11–20 μm) which are known as fast-conducting corticospinal fibers (conduction around 50 m/s). CST fibers for the upper limb are more medial than lower limb fibers. The rest of the CST fibers synapse on other interneurons within the gray matter of the spinal cord. The large CST fibers are essential for eliciting MEPs. About 55% of all CST fibers end in the cervical region with 25% innervating the lower limbs. The rest of the fibers innervate the thoracic region. It

is interesting to note that the CST is not symmetric, and it appears that CST fibers that cross more anterior tend to form the larger proportion of CST fibers in the cord whether it is the right or the left [25]. A single αMN has over 1000 synapses with over 50 direct inputs [26]; thus in the awake animal, generation of an action potential in the αMN is a complex process of competing systems. In the anesthetized animal, this complex system is shut down due to anesthetics. In addition to αMN CST inputs, there are inputs from interneurons driven by other CST fibers, inhibitory interneurons, Renshaw cells (which are inhibitory), sensory Ia and Ib fibers, and other descending tracts including the rubrospinal tract, vestibulospinal tract, reticulospinal tract, and tectospinal tract. Many of these presynaptic fibers synapse at multiple locations on the αMN, instead of one point. Due to the large number of synapses, it appears that the control of the αMN is multifactorial. In the non-neurologically compromised awake human, all the synaptic inputs to a specific αMN modulate the membrane potential; thus appropriate supratentorial modulation appropriately depolarizes the cell.

The CST enters the gray matter of the spinal cord in the ventral horn and fans out terminating in laminae IV through IX [27]. Yet the largest CST fibers appear to make monosynaptic connections to the αMN in laminae IX [28]. Most of the CST tends to synapse on interneurons, some of which being part of circuits that modulate the αMN, while others influence motor circuits such as the γ-motor system. Axons from the αMN innervate muscle fibers of a single muscle. The αMN and its axon are known as the lower motor neurons. The combination of the αMN, the terminal branches of the αMN, and the muscle fibers they innervate is known as the motor unit. Each motor unit is innervated by one axon and thus only one αMN. See Chap. 8 for more information on the motor unit.

Damage to either the upper motor neurons or the lower motor neurons will cause paralysis. Damage to the lower motor neuron will result in what is known as a flaccid paralysis—no muscle tone and no movement. Damage to the upper motor neuron demonstrates a more complex set of symptoms but generally includes no voluntary movement and a range of muscle tone from minimal tone to severe spasticity.

Indirect damage to the motor system can arise from reducing the blood supply to the critical structures. The cortex is supplied primarily by four main vessels, the two carotids and the two vertebral arteries. These four vessels supply the circle of Willis (COW) presenting connection between the carotid and vertebral arteries. The middle cerebral artery (MCA) coming off of the carotid artery supplies the lateral frontal and central cortex and its descending axons as well as much of the temporal lobes. The anterior cerebral artery (ACA) supplies the medial parasagittal frontal and central cortex and its descending axons originating from the motor cortex. Axons of the CST within the internal capsule are supplied by lenticulostriate branches originating from the MCA and the anterior choroidal arteries. At the level of the brainstem, the CST is supplied by branches of the vertebral and basilar arteries. The spinal cord is supplied by one anterior spinal artery (ASA), two posterior spinal arteries (PSA), and a varying number of radicular arteries. The ASA supplies the anterior 2/3 of the spinal cord including the lateral and anterior CST and the ventral horn. In the adult, the ASA is formed via fusion of the anterior spinal branches of the vertebral arteries, while the PSA originates from the posterior inferior cerebellar arteries (PICA) [29]. In the thoracic spinal cord, there is usually one large supply vessel coming from the aorta known as the artery of Adamkiewicz and two or three smaller vessels. Interestingly, in about 10% of patients, this vessel enters the spine at the L1–L2 level [30]. This variability in supply demonstrates one of the critical needs for neuromonitoring. Normally watershed zones are most commonly seen at levels T1, T5, and T8–T9 where reductions of blood flow in any of the feeder vessels can cause significant ischemia at these regions [29].

Electrophysiology

Electrical stimulation is used to generate APs in multiple points along the motor pathways. There are, in general, two types of recorded response in the anesthetized patient: (1) conducted volleys traveling along the spinal cord and peripheral nerves and (2) compound muscle action potentials (CMAPs). The latter one records the muscle response activated from excitation of the αMN. In general stimulation is applied at the level of the motor cortex or subcortical part of the CST, the spinal cord, or peripheral nerve. Each of these areas requires different stimulation parameters that will be described in the next section.

The descending volleys along the CST, initiated via stimulation, originate from separate but not independent circuits and are differentiable by their responses. The first response, defined as the D-wave (Fig. 7.4), or direct response, results from the direct stimulation of the CST fibers in the cortex. This response can come from either stimulating the axons directly or also stimulating the gray matter in turn generating the axonal response. During IONM procedures, it is the axon that is being activated. The second set of responses are defined as I-waves, or indirect waves (see Fig. 7.4), resulting from local circuits in the cortex being activated by the stimulus. It has been shown that the amplitude of the D-wave is proportional to the intensity of the stimulation of the subcortical white matter up to a certain point, which most likely represents the activation of the entire CST [32]. It was also observed that the latency does not increase linearly as stimulation intensity is increased. Late in the 1980s, Rattay demonstrated that the point of action potential initiation on an axon most likely occurs at bends or curves [33]. These sudden *jumps* in latency correspond to the location of CST bends which occur at the fan out of the fibers in the cortex, at the level of the genu of the internal capsule and at the level of the brainstem. This fact is important since if surgery is targeted at a specific area in the brain, you need to make sure that the stimulation does not directly activate CST fibers more caudal in the brain or brainstem from the point of surgical intervention.

Given that D-waves result from a direct activation of the cell body or axon, and the fact that the response is recorded from the axon, these responses are unaffected by anesthetics. I-waves, on the other hand, will usually not be present during certain forms of anesthetics given that they are generated via circuit pathways and contain multiple synapses. For many surgical procedures, such as during spinal instrumentation procedures, recording descending volleys along

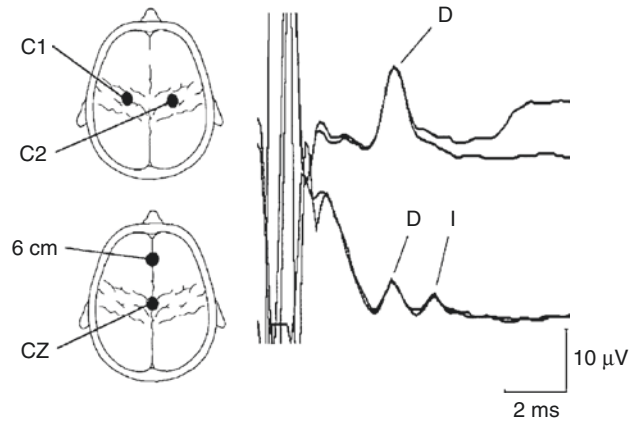

Fig. 7.4 Upper thoracic epidural recordings of D- and I-waves in a 14-year-old female during surgery for a low cervical intramedullary tumor. The upper trace was obtained after transcranial electrical stimulation over C1 (anode) and C2 (cathode) using 140 mA stimulus intensity and a stimulus duration of 500 µs. The lower trace was obtained after anodic stimulation at Cz and cathodal stimulation at 6 cm anterior to Cz, using the same stimulus duration but at 200 mA. Note the appearance of the D- and I-waves with this electrode arrangement (An upward deflection is negative). (Reprinted with permission from Deletis [31])

the CST is considered an invasive procedure and is not used. During most surgical procedures, muscle responses (known as CMAPs), resulting from driving the αMN via the largest fibers in the CT, are the monitored waves. Given that the αMN is a highly modulated cell, the effects of anesthesia are important in understanding the behavior of the CMAP response. As anesthesia starts to shut down synaptic transmission, it becomes increasingly difficult for a single pulse on one CT fiber to be able to generate a CMAP (although in some cases high-intensity long pulse stimulus durations will generate a CMAP). In order to compensate for the effect of anesthesia, it was found that a multi-pulse technique was necessary. It is important to remember that the multi-pulse technique is needed for generation of a CMAP, but the D-wave can be generated with a single pulse. It is interesting to note that when under deeper anesthetic states, I-waves are lost, thus giving credence to the synaptic nature of I-waves. When looking at the different anesthetic agents, it has been demonstrated that inhalational anesthetics are the most effective in abolishing the muscle MEP response [34–37]. It should also be noted that the blocking effects of inhalational anesthetics are not linear at the αMN; thus the interstimulus interval (ISI) between train of stimuli will need to change as concentrations change [35, 36]. Sloan et al. demonstrated that for low to moderate doses of isoflurane and N_2O, an ISI between 3 and 6 ms was optimal for producing CMAPs, yet for high concentrations only 1 ms ISI produced a recordable CMAP. Given that they studied using N_2O alone and found no major difference between the concentration and ISI, they concluded that isoflurane was the primary cause of the reduced CMAP amplitudes. At our institution we find that shorter ISIs help elicit MEPS when higher doses of inhalational agents are used and make less of a difference with a pure TIVA regime. A common technique to minimize the anesthetic effect at the αMN is to use an infusion of opioids with propofol. Even though this technique can still affect the CMAP response, its effect is much smaller than that of inhalational agents. Scheufler et al. investigated varying doses of propofol (combined with a constant remifentanil infusion) with different ISIs and stimulus intensities and found that an ISI of 1 ms produced the largest MEP response for a given dose of propofol [38]. It is important to note that in some cases, for patient safety, a specific anesthetic may be needed that is not optimally compatible when eliciting MEPs, and it is critical that the IOM technologist and neurophysiologist have a good line of communication with the anesthesiologist and surgeon.

There are additional pulse parameters that can help overcome the anesthetic effect at the αMN. The multi-pulse technique consisting of a train of 5–9 pulses and an ISI of 1–4 ms is the primary method. Some groups [39] describe using a 500 μs pulse width, while some IONM equipment does not allow for stimulation pulse widths above 75 μs.[1] Recently, Abalkail et al. investigated pulses with optimization via strength duration curve analysis and found that a pulse width of 200 μs is optimal when using a 4 ms ISI [40]. In 1993, Taniguchi et al. studied multiple stimulation parameters during craniotomies [41]. Using both cathodal and anodal monopolar stimulation, Taniguchi et al. looked at stimulation pulse width, train length, and ISI. The study found that an ISI of 2 ms was optimal (i.e., minimal stimulation intensity to obtain a maximum MEP response) yet varied with age, anesthetic regime, and functional integrity. It is important to note that they did not do a systematic strength duration analysis though. Using these results some groups have demonstrated that when a non-optimal MEP is obtained, one should try varying the ISI (Journee et al. personal communication). Varying the ISI is important since for the αMN to reach firing threshold, the temporal relationship between the D-wave volleys is critical. Deletis et al. found that short trains with an ISI of 4 ms were optimal in eliciting responses in the tibialis anterior muscle (TA) based on complete recovery of the D-wave amplitude [18]. It is important to note that Taniguchi et al. used a 200 μs pulse width, while Deletis et al. used a 500 μs pulse width which may affect the optimal ISI. Deletis

[1] At the time of this writing.

et al. demonstrate that if the ISI is a harmonic of the regular I-wave intervals, it will require less stimuli to be able to generate I-waves and in turn a CMAP, even though this may not be easy to determine in the OR other than by trying differing pulse widths if the response is difficult to obtain [18]. Szelenyi et al. found that an ISI of 4 ms always produced MEPs at the lowest stimulation threshold, yet the difference between the different ISIs was not statistically significant [42].

Another technique used to improve the efficacy of the CMAP is to use a conditioning pulse train [43]. The motor response recorded in the operating room is a combination of responses from multiple motor neuron pools. Each pool is directly activated by a single corticospinal axon. If all motor neuron pools are activated simultaneously, it would be easy to just modify the number of pulses in a train in order to elicit the maximum MEP amplitude. In most cases the motor neuron pools do not activate simultaneously when either giving a single pulse or single train of pulses due to dispersion (i.e., uneven conduction along the different fibers) between the fibers, even at supramaximal stimulation while under anesthesia. This dispersion has the effect of increasing the time difference between pulses arriving at the motor neuron pool. When there is a lesion in the fiber pathway, this dispersion effect increases. Thus, in many cases during surgery, the optimal MEP amplitude is not met due to abnormalities in the spinal cord fibers' conductivity or impaired spinal cord function. The purpose of the conditioning pulse train is to raise the αMN membrane excitability. This pre-pulse train (conditioning pulse train) facilitates the generation of the CMAP via the actual test pulse train by making it easier for the test pulse train to depolarize αMN. This technique is based on the the following two properties: (1) increaseing the membrane excitability (depolarizing the alpha motor neuron membrane) via direct activation of the corticospinal tract; and (2) via secondary neurons activated by temporal summation. In order to optimize the facilitation, the test stimuli need to be applied just when the αMN membrane is maximally depolarized from the conditioning train. Journée et al. developed such a methodology whereby a pre-train is applied prior to the test train to raise the excitability of the αMN [43].

It is known that the motor threshold of a muscle during a voluntary contraction is lower than when that muscle is at rest and that this difference is modulated by both cortical and spinal mechanisms [44]. These voluntary mechanisms used to reduce motor threshold cannot be used when the patient is anesthetized. By using homonymous conditioning (stimulating the same pool at the same site for both the conditioning and test pulse train), there is the potential for a large overlap between the motor pool stimulated with the conditioning pulse and the test pulse. Journée et al. describe two windows for facilitation: (1) with an intertrain interval (ITI) between 10 and 40 ms and (2) with an ITI >100 ms. It is recommend trying the shorter ITI first and then the longer ITI [43].

Transcranial Motor Evoked Potentials

TES and TMS are both used to activate the motor system and elicit MEPs. The two techniques differ in their location of action on the neuron. With electrical stimulation the electrical current flows from the anode to the cathode, and the predominant direction of flow is in the radial direction, while for magnetic stimulation, the magnetic field passes perpendicular to the plane of the coil which is placed tangential to the scalp (see Fig. 7.2). The electric field produced by TMS is perpendicular to the magnetic field and thus tangential to the cortex. Thus for each type of stimulation, the electric field is oriented 90° from each other. When the electric field is parallel to the neural element, activation is a function of distance and also changes in orientation (i.e., not exactly parallel) of that element with bends being the most likely sites of activation [45, 46]. The TES response is at a slightly shorter latency than the TMS response [47]. The latency difference is a function of the trans-synaptic nature of TMS activation versus the direct activation of CST fibers when TES is utilized. As described above,

when TES is applied in the awake animal, there is both a direct response (D-wave) from direct activation of the CST axons and also I-waves from indirect synaptic activation of the CST axons. Differing orientations of the coil will generate a response at differing latencies with respect to the D-wave produced by TES [48].

In the 1830s, Michael Faraday found that when a pulse of current is passed through a coil of wire, a magnetic field is generated. If a secondary conductor is nearby (within the induced magnetic field), a current is induced in this conductor that is related to the rate of change of the magnetic field [46]. When stimulating the brain using TMS, a coil is placed over the subject's head, and a brief pulse (usually around 100 μs) is passed through that coil generating a magnetic field that is large enough to pass through the subject's skull inducing a current within the brain. It is critical to point out that it is not the magnetic field that is directly stimulating the neural elements, but the secondary currents in the neural elements via induction. TMS has been tried during some surgical procedures [49], yet from a practical point of view due to the trans-synaptic nature of CT neuron activation, and the overall size of the stimulating element, TMS is not a suitable tool.

Electrical Elicited MEPs

The most common technique to elicit MEPs in the OR is via electrical stimulation applied to the scalp and/or exposed cerebral cortex and then to record the CMAP from the muscles. Using this technique, the functional integrity of both the CST and CBT can be continually monitored. The stimulus is applied over the motor cortex and recorded from the muscle or directly over the spinal cord. The montage and polarity used to apply the stimulation dictate the focalized nature of the stimulus, the laterality, and the extent of the artifact. For transcranial stimulation the montage can be categorized into bilateral (interhemispheric and midline) or unilateral (intrahemispheric). Using the international 10–20 EEG system, the standard MEP-stimulating electrodes are placed over the motor strip, and these are approximated with electrodes at positions C_1, C_2, C_3, C_4, and C_z, while for midline stimulation, having the cathode 6 cm anterior to C_z is also one possibility especially when muscle motor twitches disturb surgery. It should be noted that MacDonald recommends placing the leads a little more anterior to the standard central 10–20 locations and designates these as "M" locations [50]. The most common montages are the interhemispheric $C_1/C_2(C_2/C_1)$ and $C_3/C_4(C_4/C_3)$ montages. Making either C_1 or C_3, the anode will preferentially stimulate the CST fibers originating from the left hemisphere, while making either C_2 or C_4, the anode will preferentially stimulate the CST fibers originating from the right hemisphere. The $C_3/C_4(C_4/C_3)$ montage is able to elicit muscle responses in all four limbs but is preferential for monitoring upper limb MEPs, while the $C_1/C_2(C_2/C_1)$ shows a preference for the lower limbs, yet once again is able to elicit responses in all four limbs. The C_3 and C_4 montages have demonstrated the muscle activations with the lowest motor threshold in all four limbs [42] which might make it appear to be the most optimal for most MEP monitoring. An alternative is C_1/C_2 or C_2/C_1. C_3/C_4 and C_4/C_3 montages are known to cause large movement artifact. Instead of a focal stimulation, the stimulus is spread over a much larger area, in turn potentially activating many more fibers. Starting with the $C_3(C_4)/C_4(C_3)$ montage, due to it having the lowest motor threshold, is a good solution. Yet, it needs to be kept in mind that this montage has the potential of deeper current penetration, and thus in supratentorial surgeries, such as aneurysm surgery, the stimulation point may be caudal to the site of the surgery and therefore can miss a lesion to the CST. In this case using the $C_1(C_2)/C_2(C_1)$ montage may be more appropriate. Generally, in brain surgeries, direct stimulation of the exposed cortex via strip electrode is the method of choice. There are also other more focal montages such as the unilateral intrahemispheric C_3/C_z and C_4/C_z or the midline C_z/6 cm anterior to C_z. The $C_3(C_4)/C_z$ montage was shown to be appropriate for eliciting upper limb responses but was very poor in eliciting lower limb muscle responses. The $C_3(C_4)/C_z$ montage is the method of choice when eliciting corticobulbar responses such as those recorded from the vocal muscles

[51] or the facial muscles [52]. The focal montage is superior to that of the interhemispheric montages since direct stimulation of the facial nerve itself can occur with the larger spreading montage, without actually stimulating the CBT. This response may also give a false sense of security since the stimulation location may be distal to surgery and thus give false-negative results if the injury occurs proximal to the stimulation point. To exclude the possibility that the current spreads distally and directly activates cranial nerves, and not corticobulbar fibers, the use of single stimulus versus train stimuli is needed [51, 53]. Finally in a rare set of patients, using the midline montage of C_z/+6 cm to C_z may be beneficial for eliciting muscle responses from the lower limbs, yet the stimulus intensity needs to be high.

Stimulation intensity varies along with the MEP technique used. A theoretical calculation by MacDonald et al. showed that using pulse widths between 50 and 800 μs should allow for safe stimulation (below the level of damage to neural tissue) and that using a pulse width of around 200 μs is optimal for energy minimization based on the rheobase and chronaxie of the stimulated neural elements [40, 50]. It should be noted that each patient is somewhat different, and patient-specific physiology, disease state, and the patient's own response to anesthetic will affect the optimal stimulus parameters although the above ranges are good starting points.

At present there is no generally accepted ISI or train length as a standard for eliciting MEPs. Increasing the overall number of pulses within the train can reduce the stimulation threshold. It is also known that in some patients under light anesthesia, MEPs recorded from the muscles may be elicited by using one or two pulses, but in general the use of five pulses appears to be a good starting point [31]. Yet the use of more pulses (6–9) [54] or less pulses (3–4) [55, 56] is reasonable. Dong et al. [53] reported using three pulses when eliciting CBT MEPs. ISI starting points are also variable with the starting point ranging from 1 ms up to 4 ms. Szelényi et al. showed that using an ISI of 4 ms can minimize limb MEP thresholds [42], although using ISIs of 1 and 2 ms has shown to be best for both upper limb and CBT MEPs [50, 53, 57]. It is also worth mentioning that using an ISI of 2 ms is recommended for eliciting CBT MEPs because of their rather short latencies.

In the authors' experience, a pulse train of seven pulses with an ISI of 2 ms and a pulse width of 75 μs is a reasonable starting point for generating limb and CBT MEPs. Yet as discussed by MacDonald et al. [50], individual patient characteristics and anesthetic conditions may require altering of the parameters to get an optimal MEP response.

Direct Cortical Stimulation

In addition to transcranial stimulation for eliciting muscle MEPs, one can also stimulate the cortical surface [58–61] or subcortical space [62] directly. In order to help localize the motor strip, mapping the location of the SSEP phase reversal is recommended and described elsewhere in this book. For direct cortical stimulation (DCS), it is highly recommended to use a four- to eight-contact strip electrode placed over the specific region of interest. In cases where the motor strip is exposed, using a stimulation probe to localize the motor cortex is recommended since this will help guide the placement of strip electrode. In some cases, such as during aneurysm surgery, it may not be possible to directly test the cortex since the strip is usually placed under the skull due to that region not being included in the exposure. Thus for MCA aneurysm procedure, the strip would be placed over the lateral motor strip, while for ACA procedures, the strip is placed more medially. The cathode is placed at FPz (or as close as possible) with the anode (active, stimulating electrode) being one of the electrodes on the strip. Similar stimulation parameters to TceMEPs are used for DCS stimulation except that stimulation intensity should not exceed 25 mA [58]. In this study published by Szelenyi et al. [58], they were able to record MEPs from DCS in 84% of cases. Reasons for not being able to elicit MEPs with this method include seizure, brain swelling, premature aneurysm rupture, subdural scars, and patients with an aneurysm in the posterior circulations (it should be noted that in a small subsection of patients with anterior circu-

lation aneurysms, they did not place electrodes). Dislodgement of the electrode is an issue, yet we have found that once the electrode is in place, and by securing the lead wire with a staple, dislodgement of electrode was not an issue. One of the most frequent problems is the fact that the electrode contacts may not be over the motor strip. In some cases the surgeon might try to reposition the electrode, while in other cases, this has not occurred and we were not able to elicit MEPs. Szelenyi et al. have recommended that the surgeon uses the electrodes on the scalp when the exposure does not include the motor strip—the same ones used for TceMEPs—as a guide for placing the strip [58].

Once the electrode is placed, we start testing using a stimulation intensity of 10 mA if extradural or 3 mA if intradural and slowly increasing stimulation by 1–5 mA after five trials separated by 0.5–1 s. If no MEP response appears up to 25 mA for an extradural placement or 10 mA for intradural, then we switch the stimulating anode to the next electrode. We continue this until all electrodes are tested. The electrode with the lowest threshold is the one that is chosen to be used during monitoring. If no response is noted, we let the surgeon know this. The surgeon will then either reposition the electrode strip or continue without DCS MEPs.

In addition to stimulating the surface of the cortex, subcortical structures can also be mapped [62]. The primary reason for mapping these subcortical structures is to determine how close the resection is to the internal capsule. For these cases a monopolar stimulation probe is used. Using a pulse width of 75–500 μs (note that in the United States at the time of publication, a 500 μs was not available on all IONM devices) and a train of five to seven pulses with an ISI of 4 ms, stimulation is applied through a small ball tip probe of 1–2 mm. Stimulation intensity was increased to a maximum of 22 mA or until a muscle response was noted [62]. As the resection approaches the internal capsule, the threshold for CMAP activation reduces. It has been reported in the literature [63, 64] that the response to distance is 1 mA ≈ 1 mm. Thus for every decrease in stimulation intensity by 1 mA, the resection edge is 1 mm closer to the internal capsule. For distances greater than 5 mm between the resection cavity edge and the internal capsule, this ratio is acceptable. Yet, as the resection cavity becomes less than 5 mm away, the distance to threshold values becomes more nonlinear eventually approaching an asymptote (i.e., a minimal stimulation current needed to generate a response even if the probe is directly on the nerve). Seidel et al. demonstrate this effect by showing that as the threshold decreases to less than 3 mA, there is a significantly greater number of patients with permanent postoperative neurologic deficits compared to when the threshold stimulation amplitude is greater than 3 mA [62].

MEPs Recorded from the Muscles

Standard MEP monitoring uses the application of a stimulus at the head and the recording of potentials either from the spinal cord or muscle(s). The stimulus is applied via electrodes placed on the scalp for transcranial stimulation, overlying the dura, directly on the surface of the brain, or in the subcortical space. For transcranial stimulation, the subject matter of this chapter, gold cup electrodes, needle electrodes, or "corkscrew"-shaped electrodes could be used. Presently needle electrodes are the most commonly used, yet historically corkscrew and gold cup electrodes were preferred. Modern needle electrodes are of low impedance (around 400 Ω) which Journée et al. demonstrated [65]. MEP threshold is linearly related to impedance above 460 Ω, while below that MEP thresholds are constant [65]. Both the standard gold disk and the older needle electrode impedances are 800 and 1200 Ω, respectively. These electrodes are applied using the standard international 10–20 EEG system.[2] MacDonald et al. recommended

[2]Stimulation directly on the brain surface or dura uses other specially designed or modified electrodes and significantly lowers stimulus levels; otherwise the parameters and montage for stimulation are very similar. The technique of direct subcortical white matter stimulation is somewhat different in that the cathode is the stimulating (active) electrode which is different than for eliciting MEPs from the cerebral cortex.

placing the central stimulating electrode 1 cm in front of the standard 10–20 system placement of C_1, C_2, C_3, and C_4. This location better corresponds to the motor strip. The FPz electrode is at the standard 10–20 system location [57].

αMN innervated distal muscles receive the highest number of the large CST fibers and should be the matter of choice for recording limb MEPs. The most common muscles monitored are the abductor pollicis brevis, abductor hallucis, anterior tibialis, and forearm flexor and extensor carpi ulnaris. There are some situations where recording MEP responses from segmental muscle may be warranted. Such situations may include far lateral decompressions and foraminotomies [66]. In those cases the surgeon should be informed that MEPs may be less reliable due to the smaller numbers of large CST fibers innervating those muscles and also due to the potential overlapping between spinal roots [67]. Either surface or subdermal needles may be used to record muscle MEPs. The authors have found needles to be more stable and secure during long cases, yet care still needs to be taken due to the sharp nature of the needles and the fact they are not always visible to the surgical team. When using needles they should be placed in the muscle bellies about 2–3 cm apart. Table 7.1 lists a set of recommended muscles for MEP monitoring with the most likely innervation from the spinal root (the highlighted muscles are the best for monitoring general CT continuity).

When monitoring muscles innervated by the CBT, the electrode placement varies according to the muscle monitored. For muscles innervated by cranial nerves III, IV, and VI, it is preferable to use hook wire electrodes. Small needle electrodes placed in the skin parallel to each muscle are also an option, yet the selectivity and recorded EMG response are not optimal. The needles are placed in the muscle at about a 30° angle to the skin. The length of the needle should be around 1 cm. For cricothyroid (CRT) muscle recordings, either short needle electrodes or hook wire electrodes can be used. Hook wires are the recommended recording electrode since the large surface area of needle electrodes can give a false-positive or a false-negative result due to the large surface area of the electrodes recording far-field potentials from the neck muscles [51]. This *false data* may indicate that the functional integrity of the nuclei or CBT is intact when in reality that is not the case. Thus we recommend using the hook wire electrodes for recording. Hook wire electrodes placed in the vocal muscle require expertise of either an ENT specialist or anesthesiologist who is trained in this technique. For cranial nerve XII, we also recommend using hook wires in the tongue to minimize any damage from the needle due to movement which may lacerate the tongue. For cranial nerve IX, we have used both needles and hook wire electrodes in the soft pallet with equally good results. When placing needles or hook wire electrodes in the mouth for monitoring cranial nerves IX and XII, they should be placed after bite blocks are in place to minimize the chances of dislodgement of the electrodes during bite block placement.

Table 7.1 Common muscle-nerve root mappings

	Muscle	Cranial nerve or root
Corticobulbar	Orbicularis oculi	VII
	Orbicularis oris	VII
	Mentalis	VII
	Cricothyroid	X
	Vocalis	X
	Stylopharyngeus	IX
	Tongue	XII
Upper extremity	Trapezius	C4
	Deltoid	C5, C6
	Biceps brachii	C5, C6
	Triceps brachii	C6, C7
	Flexor carpi radialis	C6, C7
	Flexor carpi ulnaris	C8, T1
	Extensor digitorum communis	C7, C8
	Extensor carpi ulnaris	C7, C8
	Abductor pollicis brevis	C8, T1
	Abductor digiti minimi	C8, T1
Lower extremity	Iliopsoas	L1, L2
	Adductor longus	L2, L3, L4
	Vastus medialis	L2, L3, L4
	Biceps femoris	L5, S1
	Tibialis anterior	L4, L5
	Gastrocnemius	S1, S2
	Abductor hallucis	S1, S2
	External Anal Sphincter	S2, S3, S4

Stimulation intensity and the selected recording montage are dependent on where the stimulation is being applied. The actual stimulation current activating the neuron is the same no matter what montages we used; it is the intervening tissue that determines the actual stimulation current reaching neurons. When the stimulation has to penetrate the scalp and the skull, one needs a much higher stimulation intensity. About 80% of the stimulation energy is lost in TES. On the other hand, stimulation at the surface of the brain or at the white matter will require much lower stimulator delivered intensities due to no high impedances for passing current. Continuous MEPs elicited from the cortex are performed using a strip electrode placed over the motor area. The strip contact utilized is the anode, while a contact placed at FPz is the cathode.[3] For subcortical MEP mapping, the stimulating probe tip (the active electrode) is the cathode.

Recording of MEPs is done with a filter setting of 100–3000 Hz. We choose the 100 Hz high-pass filter to reduce the low-frequency artifact from the stimulator and flatten the response curve on the display. The low-pass filter can range from 750 to 3000 Hz depending upon the noise, yet as the filter is lowered, the high-frequency components can be lost. It is recommended not to change the filter settings during the procedure so the shape and amplitude of the waves are not modified by the filter. In some cases it will be necessary to adjust filter settings if new artifact is introduced during the procedure.

MEP Monitoring Using D-Wave

It is possible to record the traveling volley along the CST in the spinal cord during surgical procedures. This is performed by placing a disposable catheter recording electrode either sub- or epidurally both cranially and caudally to the site of the surgical intervention (Fig. 7.5). A commonly used electrode is the model CEDL-2PDINX-100 (Ad-Tech, Racine, WI) which has three 15 mm spaced electrodes. If it is physically possible, it is better to use for recording contacts 1 versus 3, but in some cases, it may not be possible to get all three electrodes to sit on the dura or the spinal cord, or in some cases, one of the contacts may fail and then another contact has to be used. D-waves are recorded with a 1–1.5 ms/Div time base, a high pass of 50–100 Hz, and a low pass of 1000–3000 Hz. Minimizing stimulation artifacts can be achieved by performing ten averages while switching the polarity during each average. The amplitude and latency of the D-wave vary depending upon the level of the spinal cord being recorded. In the cervical region, the amplitude is greatest with the shortest latency. As the electrode moves caudally down the cord, the amplitude reduces and the latency increases. The reduction of amplitude is due to the reduction of the number of large CST fibers contributing to the D-wave amplitude. The latency increase is related to the conduction speed in the spinal cord and the distance from the stimulating to the

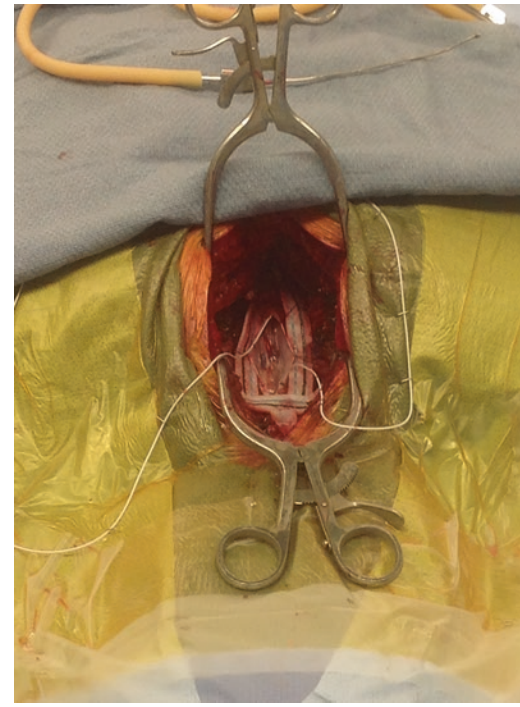

Fig. 7.5 Placement of both cranial and caudal D-wave electrodes during an intramedullary spinal cord tumor

[3] One may also use stimulation to map the cortex. This is not the subject matter for this chapter, although the techniques are similar.

recording electrodes. Other factors affecting the D-wave amplitude are related to the distance of the electrode from the spinal cord, the amount of damage to the CST, and the absolute level of the spinal cord where recording is done. Ulkatan et al. demonstrated that spinal cord anatomic position changes after correction of scoliosis can generate a false-negative D-wave amplitude change due to changes in the relative position of the epidural electrode to the CT. They also showed that no changes in the muscle MEPs occurred during epidural recorded changes indicating no injury to the spinal cord [68].

Neurogenic Response (Stimulation of the Spinal Cord with Recording from Peripheral Nerve)

Neurogenic MEPs were widely used in the 1990s but have since fallen out of favor due to the fact that there is no evidence that elicited recorded responses are generated by selective stimulation of the CST within the spinal cord [2, 69] and actually evidence proving that the response is mediated via the dorsal columns [2, 70, 71]. This technique requires the placement of stimulating needle electrodes between the spinous processes above the level of surgery (or in cases where the spinal cord or spine is exposed, one can use electrodes placed within the ligamenta flava or directly on the cord itself). For stimulation the cathode is placed caudal to the anode. Recording electrodes are applied over the sciatic nerve (or tibial nerve) in the popliteal fossa. Compound nerve action potentials (CNAPs) are then recorded. This method is based on hypothesis that CST fibers ending at αMN will be activated via the stimulation; therefore CNAPs represent activity from motor tracts [72]. It is known that antidromic stimulation of the dorsal columns [73] also activates the αMN, via branches of sensory rootlets ending up at the αMN using similar anatomic pathways that convey the H-reflex [71]. Furthermore, other motor tracts beside the CSST (e.g., the rubrospinal or vestibulospinal tracts) could activate the αMN. In fact the literature describes patients waking up with pure motor paraplegia who were monitored with neurogenic MEPs with no change in the neurogenic MEP during the procedure [2].

Indications and Contraindications for MEP Monitoring

Any surgery where there is risk of damage to the motor tracts or primary motor cortex should consider utilizing MEP monitoring. These surgeries include neurosurgical procedures in or near the motor cortex or CST and in the brain or brainstem, aneurysm clipping, or other vascular procedures that may affect the flow of blood to the motor system and also neurosurgical procedures of the spine, spinal cord, and cauda equina region. Orthopedic surgical procedures including spinal instrumentation for correction of spinal deformities, bony tumors, spinal cord decompression, and trauma and peripheral nerve entrapment correction procedures are possible procedures where MEPs are required. Vascular procedures such as carotid endarterectomy, aortic stenting, aneurysm repair, or spinal AVMs may require MEP monitoring as well. It is important to note that even with the general list mentioned above, there may be other procedures where potential damage to the motor system may warrant MEP monitoring, yet it is critical to note that given the pathology of the patient, the disease, and the goals of surgery, MEP monitoring may not be warranted, and thus every patient should be evaluated prior to surgery to determine if MEP monitoring is warranted.

Even though there is a large group of procedures where MEP monitoring may be warranted, MEP monitoring is not without its complications. Seizures are considered the second highest complication from MEP monitoring [53, 74, 75]. In 2002 MacDonald reviewed the literature and found the seizure rate for TceMEPs to be 0.03% [74]. When performing direct cortical MEP monitoring during aneurysm surgery, Szelényi et al. found a 1% seizure rate [53]. The risk for MEP-induced seizures in patients with symptomatic epilepsy was 1.5% using the high-frequency short-train mapping technique compared to the low-frequency long-train mapping technique

which was 9.5% [76]. Thus, in general, the rate of seizures is rather small, yet in those patients with a history of seizures, or pathology that may enhance its generation, immediate cessation of seizure could be achieved with irrigation of the cerebral cortex (if exposed) with ice-cold saline. This can usually halt the seizure within 5–10 s [77]. In addition antiseizure medication can be given, yet this alone can inhibit the generation of MEPs. Also, a detailed discussion should be with the surgeon so they can understand possible risks of monitoring MEPs as well as the risks of iatrogenic injury if MEPs are not used.

For both open cranial and spinal procedures (where direct access to the brain is not possible), Ativan (lorazepam), diazepam, midazolam, all benzodiazepines (barbiturates), or bolus of propofol [78] can help in halting the seizure. Yet, once a medication is given, it becomes rather difficult to record MEPs due to the cortical inhibition caused by the drug.

Lip and tongue lacerations are the most common complications of MEP monitoring and have a reported incidence rate of 0.2% [74]. Their most likely explanation is due to the contraction of the jaw musculature triggered through the motor part of the trigeminal nerve or even the CBT pathways [50]. To minimize this complication, it is highly recommended that dual bite blocks be used and placed in between the upper and lower jaw on both sides of the mouth (Fig. 7.6).

Other complications include burns under the stimulating electrodes, movement-induced injuries, transient cardiac arrhythmias, and potential damage to vascular structures with the use of electrode placed over the cortex. Burns are due to a buildup of heat between the stimulating electrode or even the recording electrodes and the skin in most cases due to the faulty cautery [74]. In cases where the electrodes are screwed into the scalp too tightly, there may be a cutoff of blood flow and thus no way for heat to be removed causing burns. The more common cause for burns is with equipment failures. If the return current, of the cautery system, or the ground of the IONM system fails, the electrodes, both stimulating and recording, may become those returns causing excessive current to pass through the small stimulating and/or recording electrodes generating burns. Any time a burn is noted during electrode removal, it is recommended that every piece of electrical equipment that comes into contact (either directly or indirectly) with the patient be checked by the hospital's biomedical engineering department/personnel. Once again this discussion should include the benefits and negatives of MEP monitoring during the procedure. Szelenyi et al. [58] stated that 2 of the 100 patients in whom DCS with strip electrodes was used had bleeding from bridging veins damaged during electrode placement. This bleeding caused no neurologic sequel in either patient.

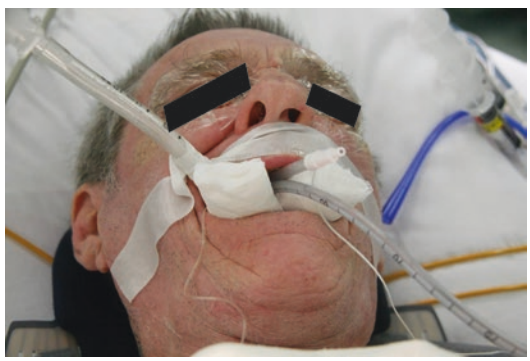

Fig. 7.6 Example of a double bite block to protect against lateral tongue lacerations

Interpretation and Alarm Criteria

Interpretation of MEP data is dependent on the location of surgery and type of surgery being monitored. What this means is that interpreting changes in MEPs during the monitoring of surgery for cerebral aneurysm appears to be different than monitoring during a scoliosis or other spinal procedures. Yet, there are some key principles when interpreting MEP changes and deciding whether criteria for an alarm have been reached. The primary alarm marker for MEPs is a change in amplitude. One of the first questions to answer is the time course of the change. Was the change gradual or was it over a very short period of time? Gradual changes tend to indicate something systemic is going on, i.e., changes in

the depth of anesthesia or blood pressure. Yet, fast changes may also be related to anesthetic effects, i.e., bolus applications of anesthetics. Thus, anesthetic and technical issues need to be evaluated very quickly during the troubleshooting. This is why it is highly recommended to continually review anesthetic concentrations and work closely with the anesthetic team to assure that any application of anesthetic is passed to the IOM team. In addition to the time course of the change, the focality of the change is also important. In general, focal changes are likely due to iatrogenic injury if all other technical factors can be ruled out. Although if working at the cervical spinal cord a systemic loss of MEPs would be due to a iatrogenic injury, an alarm should be issued immediately to evaluate the situation.

Effects of anesthesia on the MEP have been described earlier in this chapter. Yet, muscle relaxant has a significant effect on the MEP response. It is important to perform a train-of-four (TOF) test when using muscle MEPs in order to assure no muscle relaxant is in the patient's system. Some authors have described acceptable muscle MEPs when using a 2/4 TOF response. The authors find this to be an unacceptable state to monitor MEPs in. Obviously, if there is no response in any of the four twitches, then there will be no muscle MEP; the literature describes muscle MEP responses with at least two out of four twitches (see Sloan and Jantti [79]), yet given the variable nature of MEP amplitudes when not stimulating supermaximally, even in the cases when no muscle relaxant is being used, the authors recommend that no muscle relaxant be administered after intubation. It is also important to note the expected length of the procedure, since some relaxants have longer half-lives than others. This means that some relaxant such as non-depolarizing agents such as vecuronium and rocuronium will take a longer time to wash out and thus make it more difficult to record MEPs early in the procedure, where a depolarizing muscle relaxant, such as succinylcholine, will wash out much faster. In some instances the surgeons may want to have the muscles relaxed during back exposure or no movements during other exposures. Succinylcholine (SCh) is a common example of a short-acting depolarizing neuromuscular blocking agent that allows for quick recovery and monitoring of muscle MEPs. Yet, it is important to note that in cases of trauma, potassium abnormalities, malignant hypothermia, or other skeletal muscle issues, SCh should not be used [80], as well as other issues where a preoperative discussion with the anesthesiology team can be beneficial. As the muscle relaxant is wearing off, MEPs from the upper limbs will tend to return to full TOF 4/4 sooner than the lower limbs. In addition atrophied muscle or muscles innervated from damaged nerve roots may return at a slower rate than the "normal" tissue.

Basic alarm criteria for MEPs are mostly concerned with amplitude reductions. Criteria range from 100% loss to a 50% loss for spinal procedures [4, 5, 39, 80–83] and 50–60% loss for cranial procedures [58, 84] for muscle MEPs. For cranial procedures the alarm criteria of 50–60% reduction appear consistent and appropriate, yet for spinal procedures the alarm criteria are less concrete. Anesthesia primarily affects the synaptic transmission at the αMN. In addition, each TcMEP trial does not activate the complete pool of αMNs; thus for each trial, the number of excited αMNs is different which is another reason for the variable amplitude. For long cases there is a phenomenon known as anesthetic fade where the MEP amplitudes decrease over time with the stimulus level. This phenomenon is exacerbated by myelopathies. It is important to realize that this is a very slow change and not abrupt.

For epidural recordings (D-wave), the alarm criteria are more reliable. The D-wave is a function of stimulation at one point on the CST and recording at another point. The D-wave is less susceptible to anesthetic effects, and its amplitude is directly related to the stimulus amplitude (for the most part). The D-wave amplitude is proportional to the number of fast-conducting corticospinal fibers. In addition it has been shown to be very stable over time [12]. With this in mind, it appears that a 50% reduction in D-wave amplitude is indicative of cord injury and an alarm should be given to the surgical team [31, 39, 50, 85]. Yet as described by Yamamoto et al., during brain tumor surgery, a decrement of <30% is cor-

related with recovery, while there was a persistent motor deficit when greater than 30% [86]. This is in concordance with the 50% alarm criteria used in spinal surgery, given that in cranial surgery, only one hemisphere is being affected, and thus one CT is being manipulated. Thus, the surgical region location is important in choosing the appropriate MEP alarm criteria.

In addition to amplitude reduction criteria, there are also stimulation threshold elevation changes and morphology changes. Calancie et al. describe a technique that uses stimulation threshold changes to make predictions and generate alarms intraoperatively [55, 56]. Using this technique the MEP stimulation threshold is determined at the beginning of the case. A >100 V increase in stimulator delivered intensity for greater than 1 h is predictive of a poor motor outcome. Quiñones-Hinojosa et al. looked at morphology changes in the muscle MEP as an indicator or damage to the spinal cord [84]. Using this method the authors investigated the complexity (the number of peaks and troughs in the waveform) as an indicator of outcome. One of the most reliable alarm measures uses the combination of the D-wave with muscle MEPs to predict outcome while in addition offering a very stringent alarm criteria [39]. Using this technique a complete loss of the MEP and a >50% decrement in the D-wave result in a complete paraplegia, while a loss of the muscle MEP with no change in the D-wave amplitude or a less than 50% decrement will result in a temporary motor deficit [31, 39]. The shortcoming of this technique is that it requires the invasive placement of an epidural electrode which the other techniques do not. When looking at all of the factors that can affect interpretation of the MEP, it is important to note that each technique is not truly independent. Amplitude and morphology tend to be related. Thus, when the morphology changes, i.e., going from a complex polyphasic wave to a biphasic or monophasic wave, the amplitude of the peak tends to reduce as does the total energy in the wave. Another factor is the highly likely possibility of incomplete motor pool activation. Repetitive trials can help overcome this incomplete activation (Fig. 7.7). Using the paired-pulse technique of Journée et al. can help to minimize the false-negative rate experienced in the OR [43].

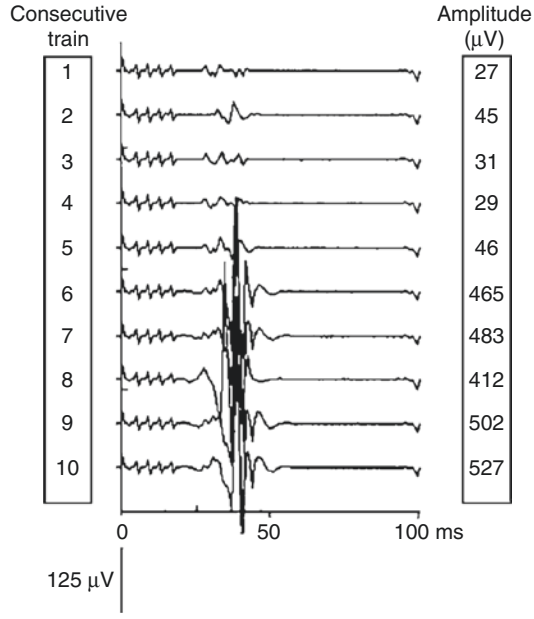

Fig. 7.7 Multi-MEP trials demonstrating the buildup effect. Note by the sixth trial the amplitude of the MEP has increased tenfold. (Reprinted with permission from Deletis [31])

Conclusion

Monitoring of the motor system, as in all IOM, is not simply looking at waveforms. Each modality, including MEP monitoring, includes special conditions that can confound the interpretation. The physiology of the motor system adds complexity to MEP monitoring by adding variability to each trial. Understanding this physiology is critical to properly performing and interpreting the MEP intraoperatively.

Review Questions

1. Describe how D-waves and I-waves work together to create activation of the alpha motor neuron.
2. How does anesthesia inhibit activation of the alpha motor neuron and what stimulation techniques can overcome this effect?
3. How can you assist a surgeon who is concerned that his tumor resection margins may be too close to the CST as it passes through the internal capsule?

4. What would you tell a surgeon if you were monitoring both TcMEPs and D-waves and saw a loss of MEP responses but a less than 50% change in D-wave amplitude?
5. Why are the most distal muscles preferred recording sites for TcMEP monitoring?

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Electromyography (EMG)

8

Aaron J. Beverwyk, Kenneth Mancuso, Amit Prabhakar, Jonathan Lissauer, Alan David Kaye, and Scott Francis Davis

Introduction

The recording of compound muscle action potentials (CMAPs) in response to spontaneous or electrically stimulated cranial nerve, spinal nerve, or ventral root activation is known as intraoperative electromyography (EMG) [1]. EMG is one of the most useful modalities for intraoperative monitoring (IOM). EMG is beneficial in monitoring neurological function in conjunction with sensory and motor evoked potentials during surgeries involving spinal manipulation and cranial nerve involvement.

Electromyographic monitoring of motor nerves during surgery allows early detection of surgically induced nerve damage as well as confirmation of the functional status of the nerve. EMG was first utilized intraoperatively in the 1960s for the preservation of facial nerve function especially during procedures involving vestibular neuromas [2, 3]. As surgical techniques improved, EMG monitoring soon became used for assessing and preserving the function of other cranial nerves [4]. In addition to its use in patients undergoing surgical procedures that place the cranial nerves at risk, it has become widely used for the IOM of spinal nerve roots during surgeries to correct various spinal deformities by providing a method of detecting changes in neural function intraoperatively [5]. One of the most popular uses of EMG in the operating room is to test the placement of pedicle screws [6, 7].

Anatomical and Physiological Basis of the EMG

A myotome is the muscle or muscle group innervated by a single nerve root. Myotomes are the motor complement to dermatomes, and myotome

A. J. Beverwyk
Neuromonitoring Associates, Las Vegas, NV, USA

K. Mancuso
University Medical Center New Orleans, Department of Anesthesiology, New Orleans, LA, USA

A. Prabhakar
Emory University School of Medicine, Department of Anesthesiology, Division of Critical Care, Atlanta, GA, USA

J. Lissauer
Department of Anesthesiology, School of Medicine, Louisiana State University Health Sciences Center, New Orleans, LA, USA

A. D. Kaye
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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distributions are also quite variable between individuals. An individual muscle may be part of more than one myotome, meaning that more than one nerve root may contribute to its innervation, such as deltoids being innervated by both C5 and C6 [1]. The axon and all of the muscle fibers it innervates are known as a motor unit. A single axon may innervate few or many individual muscle fibers. For example, a single axon may innervate a few fibers, such as the ocular muscles, or thousands of muscles, like the gastrocnemius [5]. Stimulation of an individual axon sufficient to reach the threshold for action potential firing will activate a motor unit (Fig. 8.1). This action potential at the motor unit produces muscular contraction via the sliding filament theory. The individual muscle fiber action potentials can be recorded in sum, and this waveform is the motor unit action potential (MUAP) [8]. The MUAP is the basis of the EMG recording (see Fig. 8.1).

The neuromuscular junction is the specialized synapse between the motor neuron and the muscle endplate (Fig. 8.2). The transmission of an excitatory signal is a result of the calcium-dependent release of the excitatory neurotransmitter acetylcholine by the presynaptic element into the synaptic cleft. Acetylcholine binds ligand-gated receptors on the muscle endplate opening nonselective cation channels and resulting in depolarization of the endplate. If you recall from Chap. 2, individual postsynaptic potentials summate either spatially or temporally and may result in depolarization of the endplate to threshold and the generation of an action potential.

EMG recordings are made from either surface electrodes or needles placed directly into the muscle(s) of interest [8]. Intraoperative EMG testing can involve passive muscle recordings for the purposes of detecting cranial nerve or nerve root irritation (known as spontaneous EMG or S-EMG) or may involve electrical stimulation of neural elements or hardware for the purposes of assessing function (known as triggered EMG or T-EMG). Reporting s-EMG and obtaining t-EMG responses provide the surgeon with real-time information concerning the function of cranial nerves or nerve roots [9]. In order to convey accurate information to surgeons, it is important for IOM technologists to understand the EMG innervations of these cranial nerves or nerve roots. For example, technologists should know that firing in quadriceps corresponds to L2, L3, and L4 nerve root activation, while concurrent firing in tibialis anterior and biceps femoris involves activation of the L5 nerve root (Tables 8.1 and 8.2).

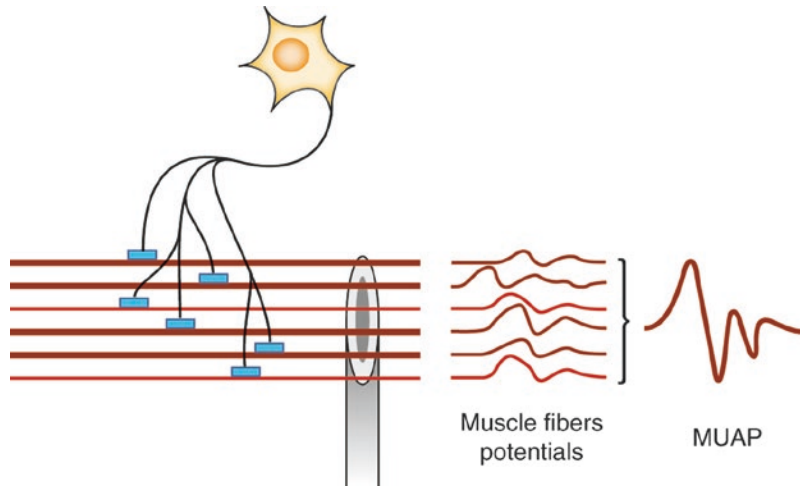

Fig. 8.1 A motor unit is shown with a recording electrode in proximity. Individual muscle fiber potentials are recorded in sum as the motor unit action potential (MUAP)

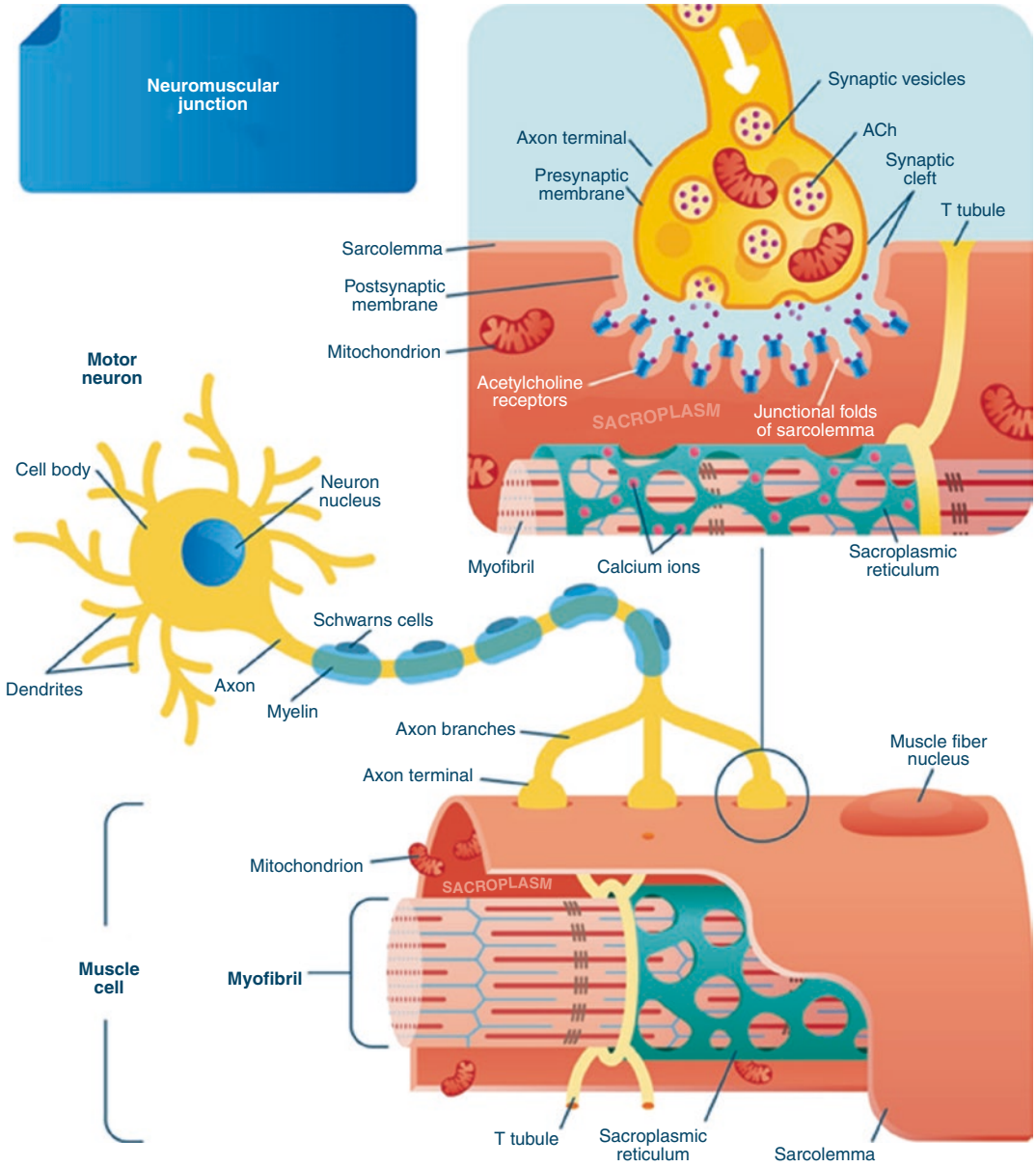

Fig. 8.2 The neuromuscular junction. (1) Action potential travels down from the axon to the endplate. (2) Calcium enters the endplate. (3) Acetylcholine is released. (4) Acetylcholine travels down the synaptic cleft. (5) Acetylcholine attaches to ligand-gated receptor. (6–7) © VectorMinelDreamstime.com

Spontaneous EMG

Spontaneous EMG (s-EMG) is used as a means of monitoring cranial and spinal nerves during surgery. The premise is that impending injury to these structures by stretch, compression, or other forms of mechanical irritation will cause them to increase firing which is detectable as CMAPs in the monitored muscle groups [9–13]. Rare firing may occur from heat/cold exposure, while ischemia usually does not induce action potential firing and thus is poorly detected by EMG. Proper

Table 8.1 Muscles used for nerve root monitoring by region

Region	Nerve root	Muscle monitored
Cervical	C3	Trapezius
	C4	Trapezius
	C5	Deltoid
	C6	Biceps
	C7	Triceps
	C8/T1	Abductor pollicis brevis/ flexor carpi ulnaris
Thoracic	T2–6	Intercostals
	T7–9	Upper rectus abdominis
	T10–12	Lower rectus abdominis
Lumbar	L1	Sartorius, iliopsoas
	L2	Rectus femoris, vastus lateralis
	L3	Rectus femoris, vastus lateralis
	L4	Tibialis anterior, rectus femoris
	L5	Tibialis anterior, biceps femoris
Sacral	S1	Gastrocnemius, biceps femoris
	S2	Gastrocnemius
	S3	Anal sphincter
	S4	Anal sphincter

Table 8.2 Recording parameters for EMG monitoring

Bandwidth	Sensitivity	Time base
5 Hz–5 kHz	50–100 mV	50 ms

selection of muscles to monitor is key to the success of S-EMG monitoring (see Table 8.1).

Many of the cranial nerves that are routinely monitored with EMG have sensory or autonomic components in addition to the monitorable motor component. In these cases, EMG is used as a sentinel for function of the entire nerve, even if the motor component is the smallest functional component of the nerve. If the motor division of the cranial nerve includes branches, it is appropriate to monitor the muscles innervated by each branch whenever possible (review Table 2.1 in Chap. 2).

Spinal nerves are mixed (sensory and motor) nerves that may be monitored for irritation with spontaneous EMG [9, 11, 13]. Spontaneous EMG monitoring differs from other intraoperative neuromuscular monitoring modalities in that the expected or normal state is the lack of response due to the absence of any muscle activity [11]. This indicates that a normal healthy nerve has not become activated as a result of surgical stimulation. Hence, reporting s-EMG to the surgeon is considered a neurological event or change.

Interpretation of intraoperative EMG depends on a familiarity of the various types of firing patterns commonly seen. Some patterns of spontaneous activity are suggestive of nerve root irritation or injury. If pre-existing nerve root irritation is present, the baseline EMG recording will often contain low-amplitude periodic firing patterns [1] (Fig. 8.3).

The clinical significance of the EMG firing pattern can be generally considered proportional to the frequency, amplitude, and persistence of the firing. Waveforms occurring at high frequency and amplitude indicate multiple motor units involved and a higher likelihood that the firing pattern is a warning of an impending injury. The correlation of EMG activity with a surgical event (such as retractor placement or hardware insertion) suggests a causative event, and reversal or cessation of the event should result in a return to the baseline EMG pattern. Persistence of EMG firing beyond cessation of the causative event is worrisome and suggests that injury to the nerve may have already occurred.

Random activation of one or a few motor units during surgery may occur with incidental contact with the neural elements and is not considered clinically significant. These waveforms are termed spikes when the activity of one motor unit is recorded or bursts when the waveform is generated by activation of several motor units (Fig. 8.4). It is important to remind ourselves that the MUAP or spike is actually the recording of a compound action potential consisting of the individual muscle fiber action potentials. As such, its morphology is distinctly different than a single action potential generated by a muscle cell or a neuron. Specifically the duration of the event is longer, often several milliseconds. These waveforms are also polyphasic as opposed to biphasic. Spiking or bursting in the EMG indi-

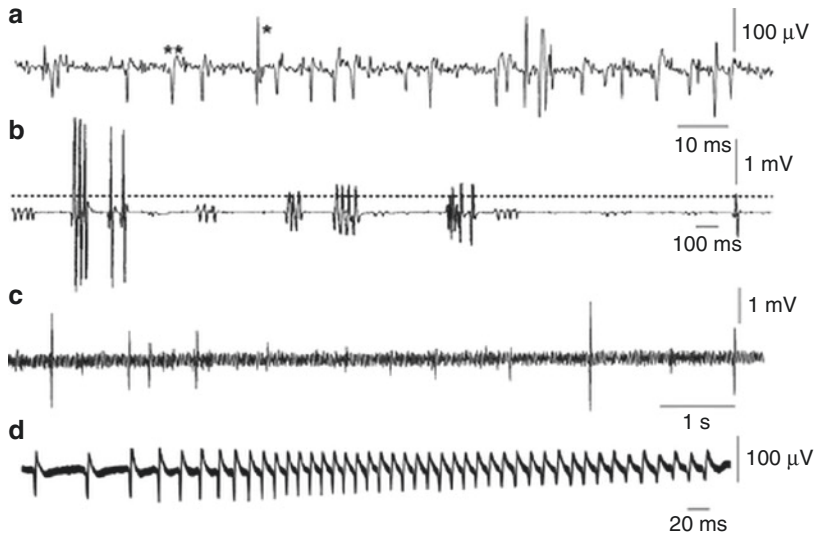

Fig. 8.3 Abnormal spontaneous activity. (A) Fibrillations (∗) and positive sharp waves (∗∗) in an acutely denervated hand muscle. (B) Single, doublet, triplet, and multiplet motor unit neuromyotonic discharges. Bursts of discharge are irregular in frequency and the intra-burst frequency of discharge is up to 200 Hz. (C) Fasciculations in the tongue in a patient with amyotrophic lateral sclerosis. The single discharges are irregular and occur on a background of ongoing EMG activity caused by poor relaxation. (D) Myotonic discharges in a patient with dystrophia myotonica. There is a characteristic waxing and waning in frequency. (Reproduced from Journal of Neurology, Neurosurgery & Psychiatry, Mills K, 76, ii32–ii35, Copyright 2005, with permission from BMJ Publishing Group Ltd)

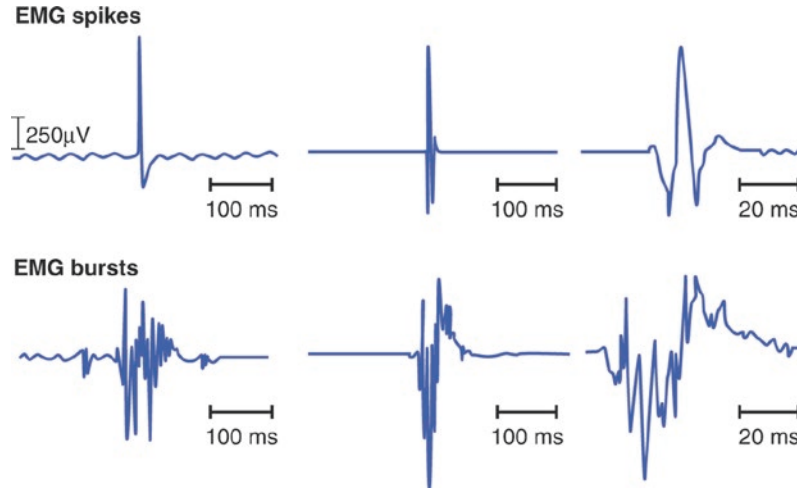

Fig. 8.4 An example of EMG spikes (*upper panels*) and bursts (*lower panels*)

cates proximity to the neural elements and may be a useful information to the surgeon while navigating the field.

Sustained activation of multiple motor units results in firing patterns with a greater degree of clinical significance. EMG "trains" are repetitive prolonged firing of one or more motor units, lasting from seconds to minutes [8]. The length of time a nerve is activated is dependent on the degree of nerve irritation [14]. Significant nerve irritation or nerve damage can produce neurotonic discharges in which no individual muscle action potentials are distinguishable [12] (Fig. 8.5). These two patterns of activity are ubiquitously

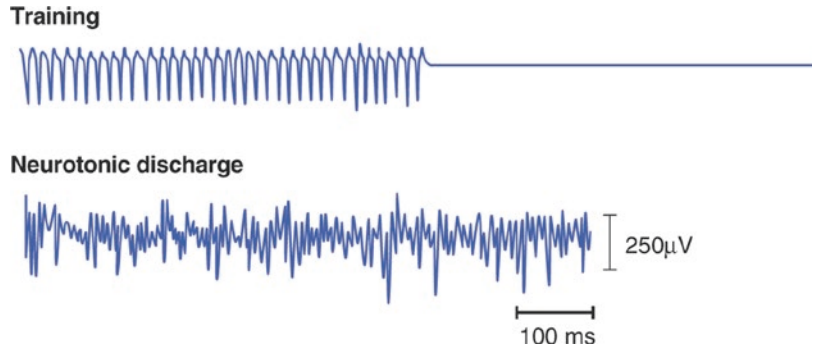

Fig. 8.5 An example of training and neurotonic discharge in an EMG recording

recognized as warning criteria for nerve or nerve root injury and should be reported to the surgeon immediately.

The use of audio output of the EMG signal is very useful to the surgeon in providing real-time data for both navigating the surgical field and warning of impending injury to the neural elements. The use of real-time audio feedback enables the surgeon to respond with immediate correction or to be more aggressive with his approach based on the data.

Triggered EMG

Triggered EMG (t-EMG) is used for three primary reasons: to identify a nerve or nerve root of interest, to assess the functional integrity of a nerve or nerve root, and to assess the placement of pedicle screws. Triggered EMG is performed with a monopolar and/or bipolar stimulating probe. Monopolar probes involve a single tip cathode referenced to a return/anode in another location (shoulder, back, etc.). Bipolar probes have the anode and cathode attached about 1 mm apart. Monopolar probes are considered "sensitive" as they can be used for regional identification of neural structures, while bipolar probes are "specific" as they are used to identify precise locations of neural structures. Typically, monopolar probes are used for pedicle screw stimulation, direct nerve root stimulation, and identification of neural structures in neuromas, while bipolar probes are used for stimulation of cranial nerves and differentiation of neural from nonneural structures [15].

Identifying Nerves and Nerve Roots

Direct electrical stimulation of a nerve or nerve root can assist in its identification. Due to redundancies of innervation patterns, accurate identification of a branch of a cranial nerve or the level of a nerve root requires specific monitoring of CMAPs using a bipolar recording montage (see Chap. 4) and a competent understanding of overlapping innervations. For example, both deltoid and biceps are innervated by C5 and C6, but deltoid has more contribution from C5 and biceps from C6.

Stimulating a nerve or nerve root directly is best accomplished with a handheld bipolar probe. A bipolar probe will reduce the size of the current field and increase the specificity of stimulation. Square wave pulses with a pulse width of 50–100 μs are delivered at a rate of approximately 2 pulses per second.

A healthy nerve should stimulate at an intensity of less than 2 mA and produce a recordable CMAP. Pathologic nerve roots (chronically compressed, injury, etc.) are those requiring stim greater than 3 mA to produce a CMAP [16]. When setting the display parameters, it is important to keep in mind both the latency and amplitude of the expected response. Most CMAPs can be several millivolts in amplitude. The latency is dependent on the distance between the stimulation and recording site. For most cranial nerve monitoring, the latency will be between 2 and 10 ms. For spinal nerve roots, the latency is approximately 15–25 ms [16].

Assessing the Functional Integrity of a Nerve or Nerve Root

Direct electrical stimulation is also used to assess the health and function of a nerve root. Healthy nerves have a stimulation threshold well under 2 mA and often under 1 mA. The use of direct nerve stimulation to provide diagnostic information concerning cranial and spinal nerves is based on the premise that previously injured or chronically compressed nerves have a higher electrical threshold for activation [16]. Interestingly, while the threshold for electrical stimulation of pathological nerve roots is higher, the threshold for mechanical stimulation is lower. This means that such nerve roots will activate more quickly while the surgeon is working in the field than a healthy root would. It is not uncommon to see increased spiking or bursting from these structures. This concept has been extended in the use of pre- and post-tumor resection thresholds for providing prognostic information about cranial nerve function [17, 18]. There are technical considerations that should be taken into account when stimulating nerves directly in the surgical field that may reduce the sensitivity and specificity of stimulation. As mentioned above, the use of a bipolar stimulating electrode is preferred for the task of direct nerve stimulation. Furthermore, it is imperative that the surgical field is dry to prevent the shunting current away from the intended stimulation target. Current shunting may result in failure to stimulate the structure or create an artificially high stimulation threshold.

Stimulating for Lateral Lumbar Fusion

Lateral lumbar fusion is a minimally invasive transpsoas approach for discectomy and fusion with minimal tissue trauma, thereby reducing recovery time. S-EMG and T-EMG are crucial in the success of the surgery as they help guide the placement of dilators and retractors by confirming the location of neural structures. In addition to helping establish a safe passage for the surgeon, EMG helps reduce complications from stretching, compression, transection, and hematoma [19].

Lateral lumbar procedures begin with initial fluoroscopy to mark a proposed pathway. The surgeon will then make a posterior incision to palpate the psoas muscle and then make the lateral incision to start dilation through the psoas down to the disc space. T-EMG is performed, typically with a clip stimulator, on each dilator to assess proximity to lumbar nerve roots. The higher the stimulation, the further the dilators are from the nerve roots. Next, a retractor is placed over the dilators, and the surgeon will perform a sweep via a ball tip probe to confirm there are no neural structures with the retractor window and also to confirm via low thresholds that the nerves are behind the retractor. Once the surgeon confirms a safe corridor within the retractor view, discectomy and fusion will begin.

Stimulating Pedicle Screws

Pedicle screws are used in surgeries for the correction of spinal deformity as well as for procedures to decompress neural elements and reduce pain and neurologic symptoms. The function of pedicle screws is to stabilize vertebral bodies following laminectomy and/or discectomy until bony fusion of the adjacent levels is complete. Pedicle screws are placed through the pedicle and into the cortical bone of the vertebral body with care not to breach the pedicle and enter the vertebral canal, causing spinal cord or nerve root injury (Fig. 8.6). Blind placement of pedicle screws without EMG or imaging guidance carries a higher risk of neurologic injury [20, 21]. Neurologic injury resulting from misplaced pedicle screws can be either radiculopathic (involving a nerve root) or myelopathic (involving the cord) damage.

Accurate placement of pedicle screws is optimized by the use of both intraoperative imaging and electromyographic guidance [6, 10, 13, 22–26].

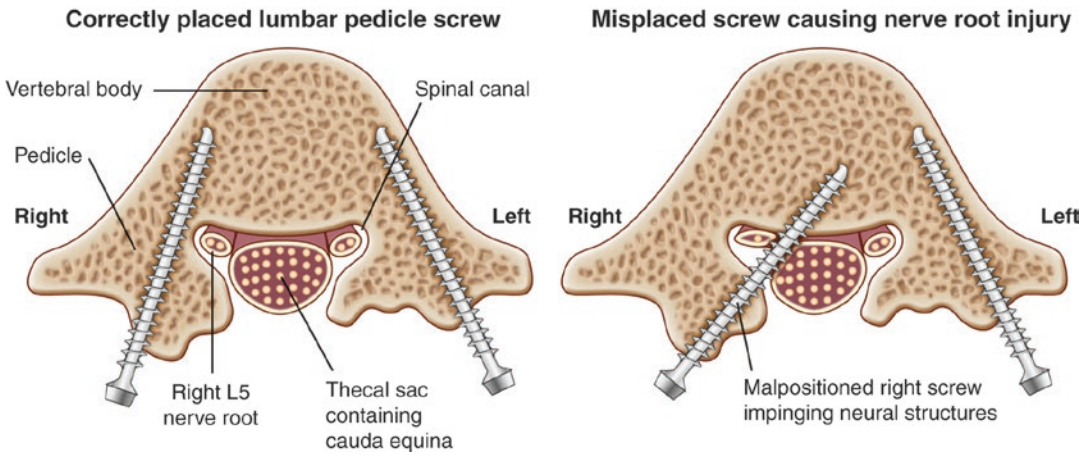

Fig. 8.6 Correctly placed and misplaced lumbar pedicle screws

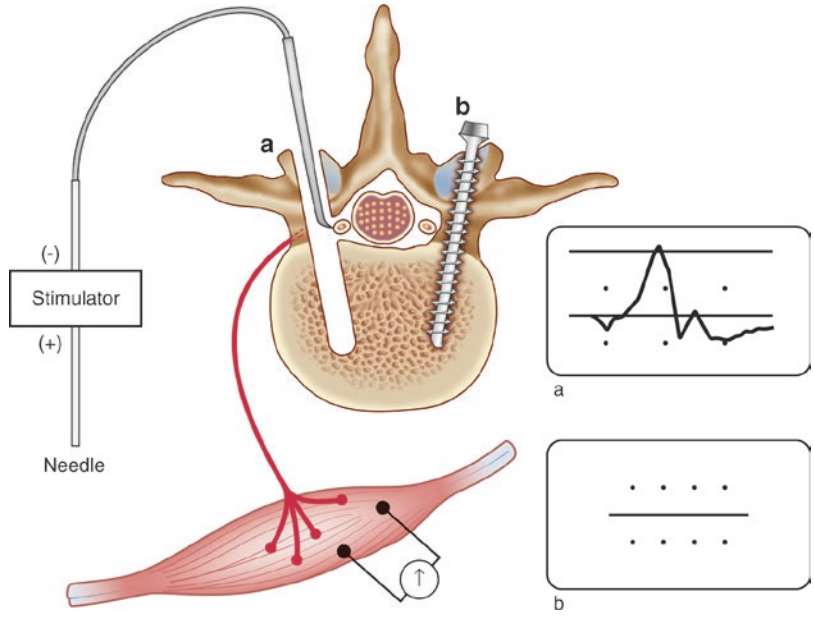

Fig. 8.7 (a) The stimulation of a screw or hole that is malpositioned resulting in a pedicle wall breach will provide a conduit for nerve root activation and a recordable CMAP. (b) A pedicle screw or hole that is placed correctly without a breach will not result in a recordable CMAP at low stimulation intensities

Imaging techniques have evolved from plain radiographs to fluoroscopic guidance and most currently intraoperative computerized tomography (CT) techniques [27–29]. Stimulation of pedicle screws cannot determine good bone purchase but instead can indicate the presence of a pedicle wall breach with reasonable sensitivity. This technique is best used together with imaging guidance and visual inspection.

The premise behind the electrical stimulation of pedicle screws to determine malpositioning relies on the fact that bone is an electrical insulator and will limit the amount of current transfer between the stimulated screw and the neural elements. A breach in the pedicle wall provides a low-resistance conduit of electricity from the electrified screw to the nerve root, which is recordable as a CMAP in the myotome of that nerve root (Fig. 8.7). If a large amount of current is required for activation of the nerve roots, it is a reasonable assumption that the bone is intact. Lower stimulation thresholds indicate a potential breach.

The stimulation of pedicle screws is commonly performed with a monopolar handheld stimulator with a ball tip. The ball tip is designed to make good contact with the head of the screw (not the outer tulip, which often results in shunting). A subdermal needle electrode is used as an return/anode and placed at a distant site such as over a bony prominence or in the abdomen. Square wave pulses of constant current are used having durations of 100–300 μs delivered at a frequency at approximately 2 pulses per second (avoiding factors of the line frequency). Since determination of the stimulation threshold is the aim of pedicle screw testing, it is imperative that stimulation starts at 0 mA and is advanced in increments of 0.5–1 mA until a response is seen. A record of the response is made (screen capture or save function) along with the stimulus threshold, and this is communicated to the surgeon.

Stimulation of the pedicle screw provides post hoc evaluation of pedicle screw placement. Another commonly used technique is the stimulation of the pilot hole prior to screw placement. Proper stimulation of the hole requires good technique in order to provide an accurate indicator of a pedicle wall breach. Proper technique involves turning the stimulator on and setting the intensity to 8 mA while moving the probe slowly up and down along the pedicular hole. If a CMAP is recorded during stimulation at 8 mA, the intensity should be reduced and the stimulation threshold should be documented. Continuous stimulation during pilot hole formation using either an alligator clip attached to an awl or pedicle access needle (PAC) or a commercially available stimulating PAC is an increasingly popular way to increase the accuracy of screw placement [30].

The interpretation of the pedicle screw testing data is not necessarily well agreed upon. Some reports advocate for an absolute acceptable threshold of 10 mA and, other more recent reports, describing the probability of having a misplaced screw when the threshold is in a particular range [24, 26, 31–33]. The reader is encouraged to explore the primary literature as it relates to this topic. The current trend in thinking is that the probability of detecting a medial wall breach increases with decreasing stimulation thresholds. CMAPs recorded at thresholds under 5 mA are highly specific for a breach (very few false positives) but poorly sensitive (a large number of false negatives) [26, 33]. The sensitivity is higher when CMAPs are recordable at stimulation intensities under 3 mA. The variable sensitivity of pedicle screw stimulation is the reason that it should remain an adjunct to imaging and not solely used to detect a pedicle wall breach.

Other factors to consider when evaluating pedicle screw testing data include consistency of thresholds between sides and vertebral levels as well as the age and sex of the patient and apparent quality of bone on examination. There is a large incidence of poor bone quality among older patients, especially females. The existence of microfractures in these patients may lower the stimulation threshold to suspect levels but should do so uniformly among sides and levels. When lower stimulation thresholds are seen on all screws, it is reasonable to assume that bone quality is playing a role. With that said, outliers compared with data obtained contralaterally or from adjacent levels should be considered clinically significant.

SSEP Versus EMG

Together, sensory evoked potentials and electromyography provide information concerning the neurological status of the spine. Separately, each modality provides differing, but beneficial, information which can be used to assess neurological issues and potentially predict postoperative complications [9, 10]. Understanding the differences in these modalities is imperative in understanding how changes are reported.

Remember from Chap. 6, SSEP are useful in predicting potential neurological complications in peripheral nerves, nerve plexuses, dorsal column tracts, the brainstem, the somatosensory cortex, and the vasculature supplying these areas. EMG, on the other hand, only supplies information concerning the motor nerve roots in the surgical area. Due to the continuous, active coverage of the neurological system by SSEP, they can be more indicative of postoperative complications.

In contrast, spontaneous EMG is a passive monitoring modality and can only relay information concerning nerve root manipulation when it causes an action potential (CMAP). However, EMG is advantageous over SSEP because changes seen in EMG are relayed to surgeon in real time, while SSEP need to be averaged over time and must show reproducible results to be considered a change, which can take minutes. When monitored in tandem, SSEP and EMG work together to provide critical information of the status of the neurological system [9, 10].

Review Questions

1. What are the pathological EMG firing patterns commonly seen in intraoperative EMG in the order of severity?
2. What is a motor unit and how do motor units differ across muscle groups?
3. What are possible explanations of baseline muscle activity recorded prior to surgical manipulation?
4. How would you dialogue with a surgeon who stimulated pedicle screws bilaterally at L4 and L5 and recorded thresholds of between 6 and 8 mA?
5. What are the advantages of multimodality SSEP and EMG monitoring. What can each modality tell you?

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9 Brainstem Auditory Evoked Potentials

Jonathan A. Norton

Introduction

The auditory brainstem evoked potential (ABEP) is probably the potential with the most names and acronyms in the field. The potential is also commonly known as the auditory brainstem response (ABR), the auditory evoked potential (AEP), the brainstem auditory evoked potential (BAEP), and the short-latency AEP [1]. However, despite its large number of names, it is one of the simpler potentials recorded in the operating room. Auditory stimulation results in a series of evoked potentials that extend for a prolonged period of time (up to 250 ms). However, in the operating room, we are predominantly concerned with the short-latency (<10 ms) responses, often termed the short-latency auditory evoked potentials. Colleagues in audiology use the longer latency potentials in their assessment of hearing [2].

Indications

The BAEP (brainstem auditory evoked potential) is widely used to monitor the integrity of the auditory nerve, but also often as a marker for brainstem health. Outside the operating room, it has been used to assist decision making concerning brain death, although this is certainly not a standard procedure [3]. To understand the indications for BAEP monitoring, we must first understand both the anatomy and the physiology of this potential. For the sake of simplicity, we will not discuss the generation of an action potential in the cochlear and auditory nerve; instead, the reader is referred to either general physiology texts or to audiology texts such as *Audiology: The Fundamentals*, by Bess and Humes [2]. Thus far, the nerve has been referred to as the auditory nerve. Formally, it is the auditory portion of the eighth cranial nerve (CN VIII) [4]. The other portion of the nerve is the vestibular portion, for which no effective intraoperative monitoring techniques exist. Both anesthesia and posture affect the vestibular nuclei. The intracranial portion of the nerve runs in close proximity to CN VII [5]. The auditory pathway consists of the classical lemniscal pathway (considered here) and an extralemniscal pathway (Fig. 9.1). The lemniscal pathway generates the short-latency AEPs through a series of "relay stations." From the auditory nerve, the first synapse of the lemniscal pathway is the cochlear nucleus. It is at this point that a bilateral response is first generated. Fibers exiting the cochlear nucleus either cross the midline and project to the contralateral superior olivary complex (SOC) or remain uncrossed and project to the ipsilateral SOC. The SOC then gives off projections that travel to the

J. A. Norton (✉)
Royal University Hospital, Department of Neurosurgery, Saskatoon, SK, Canada
e-mail: j.norton@usask.ca

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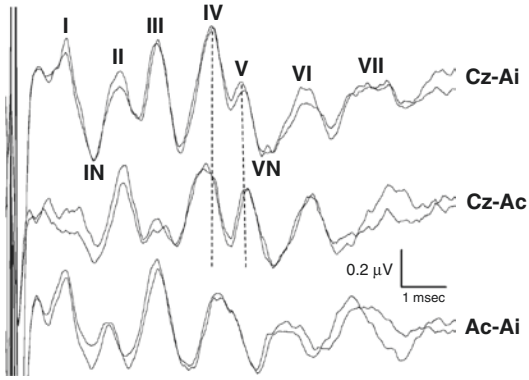

Fig. 9.1 The waveform of the BAEP can be recorded in three different montages, through the use of just three electrodes. Peaks I through to V are visible on the ipsilateral recording and II–V on the contralateral recording. Recordings from the two earlobes also allow all five peaks to be seen. The figure usefully illustrates the comparative ease of distinguishing different peaks depending on the montage selected. In practice, all of these can be easily run at the same time. (Reprinted from Aminoff and Josephson [18]; with permission from Elsevier)

inferior colliculus in a fiber tract known as the lateral lemniscus. It should be noted that there is a second bilateral projection from the inferior colliculus to the corresponding inferior colliculus on the contralateral side. The inferior colliculus sends projections to the ipsilateral medial geniculate nucleus of the thalamus. From the thalamus, fibers travel as the auditory radiations to the auditory cortex in the temporal lobe [4, 6]. This very brief review of the anatomical path of the BAEP allows us to understand some of the indications for the intraoperative monitoring of the potential. The pathway has bilateral projections early on its course through the nervous system, other than the wave generated in the auditory nerve all the other waves can be recorded bilaterally.

Tumors of CN VIII are known by a number of names, acoustic neuroma, vestibular schwannoma, and vestibular neuroma. For the most part, these tumors are derived from Schwann cells on the vestibular branch of CN VIII, so a vestibular schwannoma is possibly the best description [7]. Rarely the same tumor type can occur on the auditory portion of the nerve. These tumors are generally benign and slow growing. Many smaller tumors (or residual tumor after surgery) are treated with radiosurgery as an alternative to open surgery. Because both the vestibular portion and the auditory portion of CN VIII run so closely together for most of their length, monitoring of the BAEP is indicated in any tumor resection of CN VIII if the intent is to preserve hearing. Since posterior fossa craniotomy also places the brainstem at risk, the BAEP is also monitored as a way to detect brainstem ischemia. Bilateral BAEPs should always be recorded when possible. Although it is ideal for the IOM clinician to be able to participate in preoperative planning of these surgeries, in some instances this is not possible. If you can be part of the team preoperatively, it is helpful to know if there is any serviceable hearing left and to what degree. The patient's facial nerve function can also be documented at this time since facial nerve monitoring will be performed during this type of case as well. In non-hearing preservation surgery, there is of course no need to stimulate the BAEP ipsilaterally, but the bilateral nature of the potential allows for an assessment of the brainstem function even after destruction of the auditory nerve. Microvascular decompressions (MVDs) for a number of conditions also can pose a risk to CN VIII, either directly or through ischemic changes. MVD of CN VIII is indicated in cases where the patient suffers from either disabling tinnitus (auditory portion) or positional vertigo (vestibular portion). BAEP monitoring should also be considered for MVD procedures to relieve trigeminal neuralgia (CN V), hemifacial spasm (CN VII), or glossopharyngeal neuralgia (CN IX) [1, 7–9].

Space-occupying lesions of the fourth ventricle can disrupt brainstem function. Because of its many relay stations within the brainstem (it is called the *brainstem* auditory evoked potential after all!), the BAEP is a useful monitor of brainstem health. In my practice, the most common reason for performing the BAEP is to assess the brainstem rather than hearing. However, it is important to remember that the brainstem performs a wonderful variety of neural functions and the BAEP only directly assesses a small function of the brainstem [10]. Tumors of the cerebellar pontine angle (CPA tumors) remain

the most often indication for BAEP monitoring. Surgery to remove these tumors requires the neuromonitorist to bring their full armamentarium to the case, and that will undoubtedly involve the BAEP as well as EMG monitoring of the lower cranial nerves [11] and motor and sensory evoked potentials.

Peaks, Generators, and Blood Supply

The BAEP has five peaks or waves that are monitored in the intraoperative setting (Fig. 9.2) [12–14]. The peaks are named peak I through to peak V (wave is often substituted for peak). Peak I is generated in the distal auditory nerve, and there is comparatively little controversy about the origin of peak I. However, for the rest of the peaks, the situation is a little more complicated as each peak has more than one potential generator. We will initially consider the primary generators or at least the generators that are most commonly considered the primary generators. Peak II is generated from the auditory nerve, but in this case the intracranial portion, also called the proximal portion of the auditory nerve. The third peak, peak III, is the first that originates from the secondary neurons, meaning that they are the first peaks for which a synapse is involved. The caudal pontine tegmentum is the principal generator of peak III, as well as the negative peak between peak III and peak IV, sometimes known as IIIa. There is some evidence that there is a contribution from the cochlear nucleus to peak III as well as a contribution from the ascending activity within the lateral lemniscus. Peak III is usually not altered in individuals with lesions in the upper or middle pons, or even the mesencephalon, which is evidence that the generator lies caudal to this point. The most likely generator for peak IV is the SOC, but there is no conclusive evidence to date for a precise origin to be determined. The lateral lemniscus remains a candidate for the generator of peak IV. Peak V, the last of the BAEP peaks, is generated predominantly by the contralateral mesencephalon, specifically the inferior colliculus. The lesions of the pons and mesencephalon

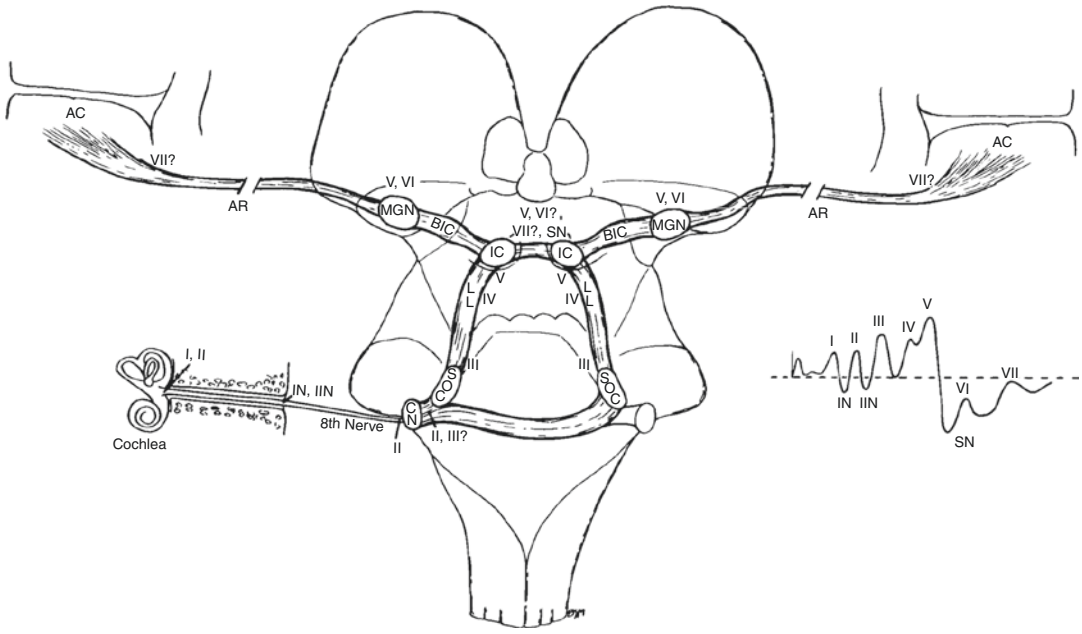

Fig. 9.2 The likely generators within the brainstem of auditory evoked potentials. The roman numerals refer to the individual peaks within the potential. CN cochlear nucleus, SOC superior olivary complex, LL lateral lemniscus, IC inferior colliculus, BIC brachium of the inferior colliculus, MGN medial geniculate nucleus, AR auditory radiations leading to AC, auditory cortex. (Reprinted from Aminoff and Josephson [18]; with permission from Elsevier)

frequently affect peak V first in the time course of the disease, and as such, this peak may be abnormal in patients undergoing surgery even when the tumor is considered to be relatively small [13]. Later peaks are not considered as part of the BAEP for the purposes of IOM at present.

Preoperative Considerations

Preoperatively, the neuromonitorist must determine the baseline hearing of the patient. Often audiologists assess this formally before the surgical procedure is planned. An appropriate stimulation level for intraoperative BAEPs can then be determined. Preoperative BAEPs may be helpful if there is time to obtain one. This is one of the easier evoked potentials to perform on an awake patient. Very few people find the process uncomfortable [3, 15]. Gathering these data before the surgery may give insight into any apparent abnormalities in the operative baseline and help distinguish between preexisting pathology and a technical issue. The size of the ear canal and whether it is occluded with earwax should also be determined prior to surgery. The presence of wax in the ear canal results in a conductive hearing deficit and will impact the monitoring data. If determined during the preoperative visit, the patient can be asked to clean their ears prior to surgery. If not discovered until the patient is seen in holding, then an ENT consult should be considered for wax removal prior to surgery or you may remove it yourself or ask the surgeon. The anesthetic regiment has little to no effect on the potential and it is the most robust to anesthesia and other systemic factors, and so any concerns or discussions with the anesthesia members of the team are more likely to focus on modalities other than the BAEP [8]. In the operating room, stimulation is usually provided through ear inserts, placed into the ear canal and connected to the electromechanical stimulator through relatively rigid tubing of a known length, and hence time-delay. The neuromonitorist in the operating room must therefore determine an acceptable location to place the stimulators that will allow them to move with the patient but out of the way of the surgeons. In practice I find affixing them to the Mayfield clamp the most reliable way of performing this important step of setup. Replacing the ear inserts if they fall out during a case can be difficult and is not going to win you much appreciation from the rest of the team.

Stimulation Clicks

Like most evoked potentials, the BAEP is a time-locked (and averaged) response to a given stimulus. In this case, the stimulus is a broadband click, generated by an electromechanical transducer. In the outpatient setting, the stimuli are pure tones of known frequency and are usually generated in the earpieces of headphones. The objective of the outpatient, clinical BAEP is to diagnose specific hearing deficits, while in the OR, the objective is to preserve gross hearing. This is the reason broadband clicks are used over pure tones in the OR. Since the large headphones are impractical in the operating room, they are replaced with small transducers and the click is delivered to foam ear inserts through stiff rubber tubing. The length of the tubing is known and therefore imparts a fixed and known delay between the electrical pulse that generates the click, which triggers the recording system, and the delivery of the click to the ear [15]. In most cases, this is a 1-ms delay. The tubing is stiff to allow for reliable delivery of the stimulus to the ear. Care must be taken that the tubing is not pierced which will reduce the amplitude of the delivered click or clamped or kinked which may prevent delivery of the click altogether [16]. It is always worth checking this tubing after positioning of the patient but before the drapes are placed. Once the inserts are placed sealing the ear canal with bone wax and placing waterproof adhesive tape over the ear will prevent fluid from entering. Each click is generated by the movement of a membrane in the transducer either toward or away from the eardrum. The direction of movement is controlled by simply changing the electrical current driving the transducer. Since the space between the membrane and the eardrum is enclosed and air cannot read-

ily escape, movement of the membrane toward the eardrum condenses the air in that space. This type of click is therefore known as a condensation click. Similarly, movement of the membrane away from the eardrum will reduce the air pressure (making it more rarefied) and so is known as a rarefaction click. In practice, both types of click sound the same on a behavioral level. Some individuals show a better response to one form of the click or another, and in those instances the optimal form should of course be used. However, for many people, there is no difference in their response (at least meaning that good, monitorable signals can be obtained from either polarity), and so the choice is left to the person running the case. It has been noted that condensation clicks can enhance peak V while rarefaction clicks may enhance peak I. There is one further option available on most modern IOM and EP machines, and that is to alternate the clicks. Alternating clicks can sometimes improve the amplitude and discrimination of the peaks (see below) and it also removes or reduces the artifact substantially. The removal (or reduction) of the artifact has its supporters as well as its detractors. As ever, the artifact serves to confirm that a stimulus pulse has been applied, although in the BAEP it is possible to get an artifact with the ear tubes out of the ear since it is the electromechanical movement that generates the artifact. However, in general, the amplitude of the artifact will be an indicator of the amplitude of the stimulation (at least the electrical trigger to the electromechanical transducer).

Parameters

There are, with all evoked potentials, a number of parameters that can be varied for the BAEP. For the BAEP, these parameters are stimulation rate, stimulation amplitude, and the polarity of the clicks as discussed above. The stimulation amplitude, measured in decibels (dB), determines the size of the evoked potential recorded. This is not a linear response, however, as stimulation below the hearing threshold will not result in any response. Above that level increases in the amplitude will give an increase in the amplitude of the response. Conductive hearing deficits have a similar effect on the recorded responses as reducing stimulation intensity. Stimulation rate has a profound effect on the amplitude of the response. As ever with IOM, there is a desire for real-time recording and interpretation, and the BAEP can be recorded adequately with stimulation rates between 5 and 50 pulses per second (pps). So why do many groups tend to work toward the lower end of the spectrum? Especially as each patient is their own control and so there is no need to conform to laboratory standards. There is an optimum frequency that compromises between speed and quality of response. Above 10 pps, the response tends to lose amplitude so most clinicians work around the 10 pps range, avoiding of course exact multiples of the local line frequency. In the outpatient setting it is usual practice to stimulate one ear at a time, and consequently the other ear has white noise played into it to ensure that only one ear is tested at a time. During surgery both ears are tested at the same time (interleaved stimulation) and so there is no need to apply masking, white noise stimulation.

Recording

The recording settings for the BAEP in the operating room are similar to those in the outpatient clinics. The high-pass filter is typically set at 30 Hz but can be increased to 100 Hz if required to reduce line noise. The low-pass filter is set at 2 kHz or a similar frequency, depending on individual machine specifications. The small size of the cortically recorded responses dictates that the larger number of responses needs to be accumulated to typically obtain reliable and repeatable records. It is not uncommon to need 1000–3000 averages to obtain a quality signal.

However, with some optimization of the stimulus, environment, and recording conditions, it is possible to need less than 200 averages in some cases. There is considerable value in trying to use the fewest averages possible to get good responses [16].

Montages

The generators of the short-latency BAEP (see above) are all deep within the brain, and so in general the recording montage is actually relatively unimportant in IOM. Since the electrodes (hopefully) do not move during a case and the patient serves as their own control, there is some latitude in montage selection for IOM, but not in outpatient clinical practice [15]. Probably the most usual configuration is using three electrodes: the two ear lobes (A1 and A2) and the vertex (Cz). Since the generators of the peaks are all distant to these recording sites, it is obvious that the exact locations are not overly important. If I am only recording the BAEP, I do not measure the vertex, but am happy to locate that electrode by "eyeball" and to move it to accommodate surgical considerations. A common alternative to the ear lobe is to use the mastoid. In these instances, the recording montage is configured A1-Cz and A2-Cz. It is always worth displaying both the ipsilateral and contralateral derivations because of the bilateral projections within the pathway. Peak I will only be visible from ipsilateral recording (often termed Ai, i for ipsilateral and therefore Ac with the c for contralateral). In contrast, peak V is most clearly visible within the IV/V complex from the contralateral recordings.

Troubleshooting the BAEP

Within the field of IOM, the BAEP is probably the most robust signal that is recorded. Anesthesia has little to no effect on the waveforms, and temperature variations within the normal physiological range have no effect on the latencies, although cold irrigation may increase latencies for a brief period of time. Variations in blood pressure have little effect on the BAEP as well [8]. The aspects of surgery have significant effects on the BAEP though. As with most IOM signals, monopolar cautery prevents the recording of the signal and can in some instances lead to a short-term saturation of the amplifiers. Bipolar cautery can be used during recordings at times but will often lead to interference on the recordings. It is less common that amplifier saturation will occur with bipolar cautery, but it should always be considered a possibility if there is a sudden disappearance of the waveform [17]. With many of the surgical procedures for which the BAEP is warranted, there is a considerable amount of bone drilling to be performed. Interference from the high-speed drill is a result of the vibration of the bones within the skull including the bones associated with hearing and less so from any electrical interference if an electrical drill is used. For an accurate BAEP, the drilling must have ceased as the vibration may result in disappearance of all waves of the BAEP. It is important that this information is communicated to the rest of the team before the procedure commences. A further potential issue that occurs during bone drilling is the large amount of irrigation that can be used. This fluid can easily find its way into the ear and even through routes that seem highly unlikely. Fluid in the ear canal will result in an attenuation of the amplitude and increase in latency of peak I. The best solution for this problem is to prevent it from happening by trying to ensure that the ear canals are watertight before draping. As mentioned previously, care must be taken that the tubing between the ear inserts and transducers is patent and not kinked. The transducers do have some mass and will tend to pull down and so should be fixed to something that should move with the patient such as the head holder.

Interpretation and Alarm Criteria

The BAEP within the operating room has a number of measured and useful parameters. Both latency and amplitude are used as alarm criteria, but the alarm criteria will be specific for any given surgery. However some principles can be used as discussed below. The first parameter to be considered is the latency of peak I. This should be 1 ms, but the addition of ear inserts and tubing will normally add a further 1 ms to the latency for a total of 2 ms. Some IONM machines automatically include the 1 ms tube delay in the recordings, so as always check your machine. There may be delays to this peak at the

commencement of the case, but these should not increase during the case. The amplitude of peak I is also measured and providing the stimulation does not change, should not change. A change may indicate a movement of the ear insert, kink in the tube or damage to the nerve. The latencies between peaks I and III and I and V (and therefore III and V) are all used as interpretive parameters. Because the peaks occur in a serial fashion for any given delay between peaks I and III, there should be the same delay between peaks I and V and no further delay added between peaks III and V. Although peak V is most easily identified in the contralateral recording (Ac-Cz), once it is identified there, it is usually identifiable ipsilaterally (Ai-Cz). This makes the latency identification relatively easy. If the peaks are identified at baseline, most modern IOM software will be able to track automatically the latencies throughout a case and alert the user when a threshold change in latency is reached. Similarly the amplitudes of peaks I, III, and V can also be tracked automatically if the peaks are identified appropriately at the commencement of the case [1]. Changes in both absolute latencies as well as changes in interpeak latencies are monitored. Conductive hearing loss or technical issues involving the stimulus not reaching the auditory nerve can cause changes in absolute latencies with no change in interpeak latencies. Intraoperative variability of interpeak latencies suggests sensorineural hearing damage or brainstem injury. A change in the interpeak latency from III to V and an absolute latency change of wave V are most concerning for brainstem ischemia as discussed below. The same principles apply to the BAEP as to most other evoked potentials in the operating room. A decrease in amplitude tends to indicate that less signal is getting through and an increase in latency indicates a slowing of the conduction velocity [1, 8]. There are a number of caveats to this general statement of course. For instance, a small increase in the conduction delay for the fastest fibers may result in a small increase in latency and a decrease in amplitude. However, the amplitude change may be a result of cancelation of some of the signals due to collision of waves, especially where more than one nucleus generates/contributes to a particular wave. Typically warning criteria are based upon the latencies of individual peaks and the interpeak latencies. An increase in the latency of peak V is considered the alarm for tumor dissection. There is very little "normal" trial to trial variability in the latencies of the peaks in the BAEP. Changes in the interpeak intervals can therefore be used to help identify the origin of the changes [8]. An isolated increase in the absolute latency of peak III in the absence of a change in peak I will lead to an increase in the I–III latency. If there is no change in the III–V latency, there will however remain an increase in the absolute latency of peak V. For this reason, it is therefore very important to keep track of not just the absolute latencies but also the interpeak intervals. The question then arises as to whether the absolute or relative latencies are the best parameters to monitor. However, as the brief example illustrates, using one or the other is not the best use of our resources and we do need to keep both in mind. Modern machines, especially if you can use a large monitor, allow for the display of tables of latencies and interpeak latencies (these are useful not just for BAEPs but other potentials). Such tables are, I find, the easiest way to track changes in these latencies and distinguish whether a change in the latency of peak V is solely due to changes in the latency of peak III. An alternative scenario, and one which is not uncommon in the case of large posterior fossa tumors, especially in the pediatric population, is that there is a global increase in the latencies. This is manifested as an increase in both the I–III latency and the III–V latency. Consequently, both peaks III and V are delayed, and the I–V interpeak latency is also increased. In these situations, the only change that might reach a critical level may be the absolute latency of peak V. However, it is wrong to therefore assume that there is a focal site of damage/injury along the III–V pathway. More likely there is a global change going on, possibly related to changes in blood flow or retraction/compression. Amplitude decreases are likely to be nonconsecutive in nature, meaning that a 25% change in peak I amplitude will not give the same change in peaks III and V. Monitoring the amplitude of all of the peaks

is therefore still required and any change of more than 25% should be reported and discussed with the rest of the surgical team. Changes greater than 50% are worrisome. However complete absence of peak V has been reported in some individuals who do not experience hearing loss upon awakening, although some authors believe that they may be at higher risk of hearing loss subsequently. If peak I is absent, then all subsequent peaks will be absent. For this peripheral peak I use the more usual 10% change in latency and 50% decrease in amplitude criteria if the surgery is around this nerve. If brainstem function is mostly at risk, data trends not yet reaching significance should always be discussed with the surgical team.

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Electroencephalography

10

Lucy R. Sullivan, Aaron J. Beverwyk,
and Scott Francis Davis

Introduction

The electroencephalogram (EEG) is a graphic display of the spontaneous electrical activity of the cerebral cortex. The EEG represents the output of a differential amplifier whose inputs are two distinct recording locations from the scalp (Fig. 10.1). Continuous EEG recordings are used clinically to diagnose brain pathology, specifically seizures. Intraoperatively, EEG is used to monitor cerebral perfusion and depth of anesthesia. Cortical SSEPs, discussed in another chapter, are brief averaged EEG epochs recorded following peripheral stimulation.

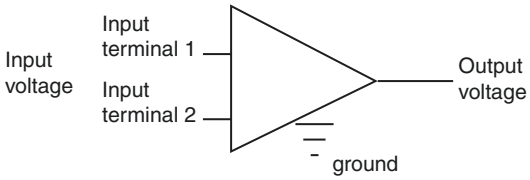

Fig. 10.1 Schematic of a differential amplifier used for EEG recording. The output of a differential amplifier is the difference between the two inputs

L. R. Sullivan
ASET, Goodson, MO, USA

A. J. Beverwyk
Neuromonitoring Associates, Las Vegas, NV, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

Discovery of EEG

Hans Berger, a German psychiatrist, was the first to record EEG in humans (Fig. 10.2). Berger initially used a string galvanometer originally designed to record electrocardiograms. The initial recordings were from patients with open craniotomies, allowing the needle electrodes Berger used to be placed only a few millimeters from the surface of the brain. The first recording through an intact human skull was performed on Berger's son. Berger's first EEG paper titled "Electrokephalogram des Menschen" ("On the Electroencephalogram of Man") was published in 1929 [1]. Berger's reports were met with skepticism mainly due to the seemingly unexplainable slow oscillations (like alpha waves) having durations of about 100 ms. Scientists were expecting the generator of the signal to be single neuronal action potentials with durations of 1–2 ms. In 1935, prominent English physiologists, Adrian and Mathews, endorsed Berger's work [2], and by 1936 there were six EEG laboratories in the United States [3].

By the 1950s, EEG was well established and the use of intracranial EEG known as electrocorticography (ECoG) was being pioneered by Wilder Penfield and Herbert Jasper to identify epileptogenic foci during epilepsy surgery [4]. ECoG is still used today to map the cortical surface for tumor resection and epilepsy surgery. Conventional EEG is also used in the OR

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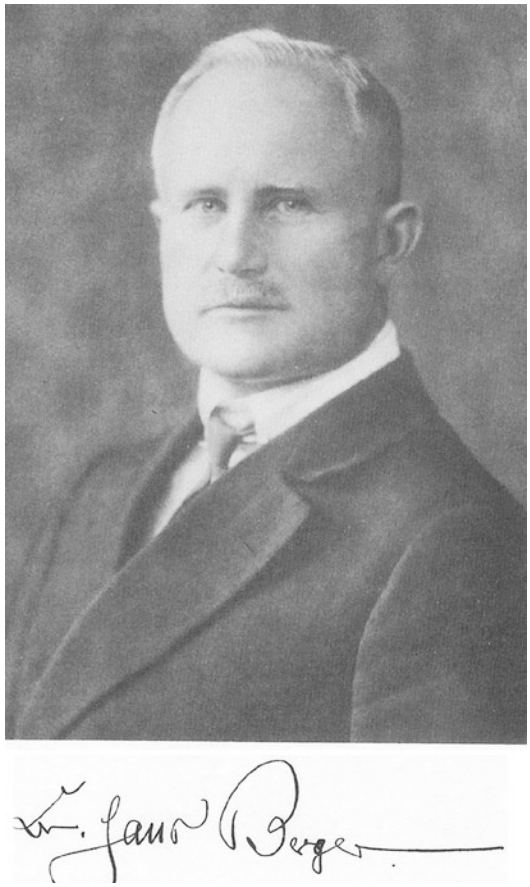

Fig. 10.2 Hans Berger (1873–1941) recorded the first human electroencephalogram

for any procedure where there is a risk of cerebral ischemia and as a means of determining anesthetic depth.

Waveform Generators/Dipoles

Postsynaptic potentials, having longer duration than the action potential, contribute to the EEG waveform [5]. As discussed in another chapter, postsynaptic potentials are either excitatory (EPSPs) or inhibitory (IPSPs) (Fig. 10.3). The EEG waveform is generated from the complex summation and integration of IPSPs and EPSPs arising from thousands of neighboring cortical neurons [6]. Pyramidal cells, mainly from layers

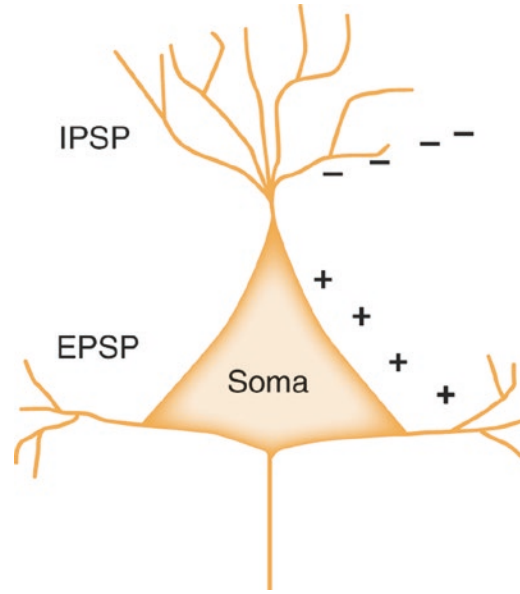

Fig. 10.3 Schematic of a neuron and the influences of postsynaptic potentials. EPSP excitatory postsynaptic potential, IPSP inhibitory postsynaptic potential

III or V, are the major contributor of these synaptic potentials, which is owed to their spatial organization within the cortex (Fig. 10.4). Being linearly arranged, these neurons have an open electrical field and produce a dipole (discussed below). The ability to record EEG depends on the synchronization of the cortical neurons. This synchronization is achieved because of the inputs from subcortical structures such as the thalamus.

Neuronal potentials have a negative and a positive field called a dipole. When the discharge is generated at the top of the cortex, it creates a radially (vertically) oriented dipole with a maximum negativity just above the source with a positive field either deep within the hemisphere or in the opposite hemisphere, depending on the orientation of the neuronal field (Fig. 10.5, panel **a**). When the discharge is generated in a sulcus of the cortex, it creates tangentially (horizontally) oriented dipoles with the fields of maximum negativity and positivity being displayed in an anterior/posterior or medial/lateral orientation (Fig. 10.5, panel **b**).

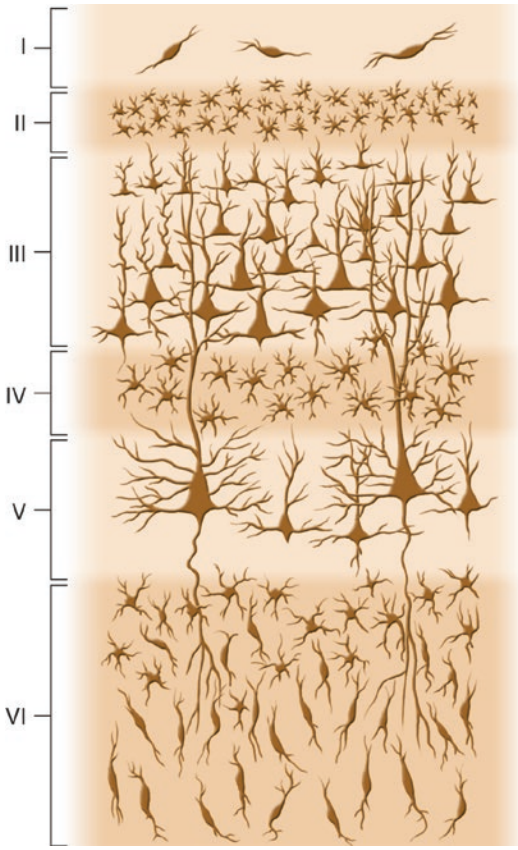

Fig. 10.4 Layers of the cerebral cortex

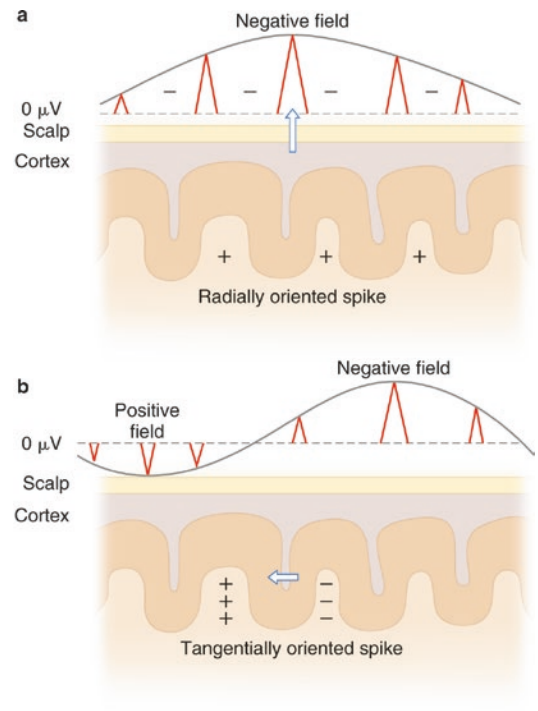

Fig. 10.5 Schematic representation of dipoles in relationship to the scalp surface. Panel (**a**) depicts a radially oriented discharge arising from the crown of the cortex with a negative field above the source and a positive field within the cortex. Panel (**b**) depicts a tangentially oriented discharge arising from a sulcus with surface negative and positive fields posterior and anterior to the source

10–20 System and Electrode Nomenclature

The International 10–20 System of electrode placement was developed in 1958 as the standard placement of scalp electrodes [7]. Anatomical landmarks on the skull are used as reference points for the measurement. The four anatomical landmarks are the nasion, the indentation between the forehead and the nose; the inion, the midline bump or ridge on the back of the skull; and the preauricular points, the indentations just above the cartilage (tragus) on the left and right ears (Fig. 10.6). Electrode designations act as binomial coordinates with the first coordinate of the designation indicating the anterior/posterior position and the second coordinate indicating the medial/lateral position. The anterior/posterior coordinates correlate with brain landmarks such as lobes or sulci. The most common designations used for intraoperative monitoring are shown in Table 10.1.

The medial/lateral electrode positioning has a numerical designation. By convention, electrodes to the right of midline are designated with even numbers and to the left with odd numbers. Electrodes on the midline are designated as "z" because they correspond to an imaginary "z line" that runs along the longitudinal fissure. The numbers increase further from midline.

In 2006, the American Clinical Neurophysiology Society (ACNS) recommended electrode nomenclature using the 10–10 system (Fig. 10.7). T3 and T4 are designated at T7 and T8. T5 and T6 are designated as P7 and

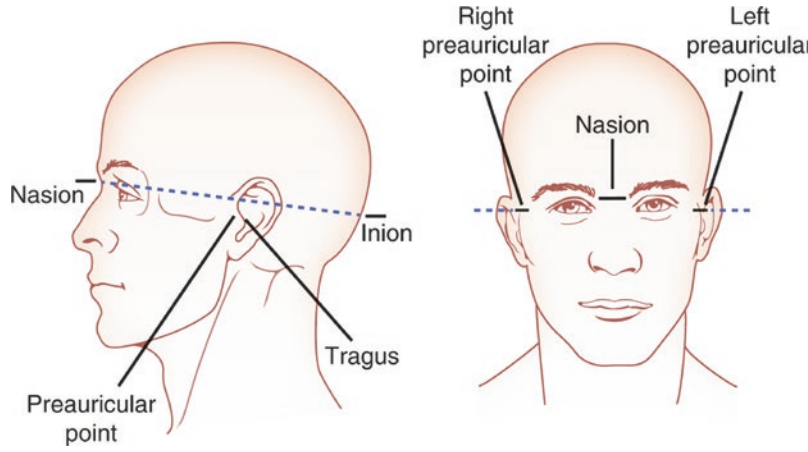

Fig. 10.6 Skull landmarks that are reference points for the International 10–20 System of electrode placement

Table 10.1 International 10–20 System electrodes most commonly used during intraoperative neurophysiological monitoring

A/P designation	Name	Description of location
Fp	Frontopolar	Over frontal pole of brain
F	Frontal	Over frontal lobe
T	Temporal	Over temporal lobe
C	Central	Along central sulcus
Cp	Central–parietal	Midway between C and P line
P	Parietal	Over parietal lobe
O	Occipital	Over occipital lobe

P8. The measurements to determine these electrode sites are exactly the same as the International 10–20 System [8].

Electrodes

Various electrode types can be attached to the scalp for the purposes of recording EEG. In a clinical setting, 4- to 10-mm metal disk or cup electrodes are most frequently used. These may be gold plated, silver, or silver–silver chloride. An electrolyte or conductive gel is placed between the electrode and the scalp to lower impedance and increase the quality of the signal. The electrode is secured with an adhesive such as collodion or paste. Desirable electrode impedances are under 5 kΩ. For intraoperative EEG, stainless steel subdermal needles are more commonly used. These can be quickly and safely inserted just under the scalp and provide excellent quality recordings. Electrode removal is likewise quick and clean! Corkscrew electrodes are similar to subdermal needles and are advantageous for cranial procedures due to the decreased ability to replace dislodged electrodes close to the sterile field.

Montages

A montage is a systematic and logical combination of multiple pairs of electrodes that are used for electrophysiological recording. An acceptable montage for EEG should compare activity from homologous electrodes between the two hemispheres. For intraoperative monitoring, there are two main types of recording montages: bipolar and referential. Bipolar montages compare active electrode sites adjacent to each other. An example of a bipolar montage used for EEG is the anteroposterior (AP) montage (Table 10.2).

Referential montages compare an active site recording a biologic signal of interest to a common reference some distance away. Ideally the reference should be inactive, meaning that it does not "see" the biologic signal of interest. Unfortunately, it is very difficult to find an inactive reference. Sites commonly used for the reference electrode include earlobes, skin over

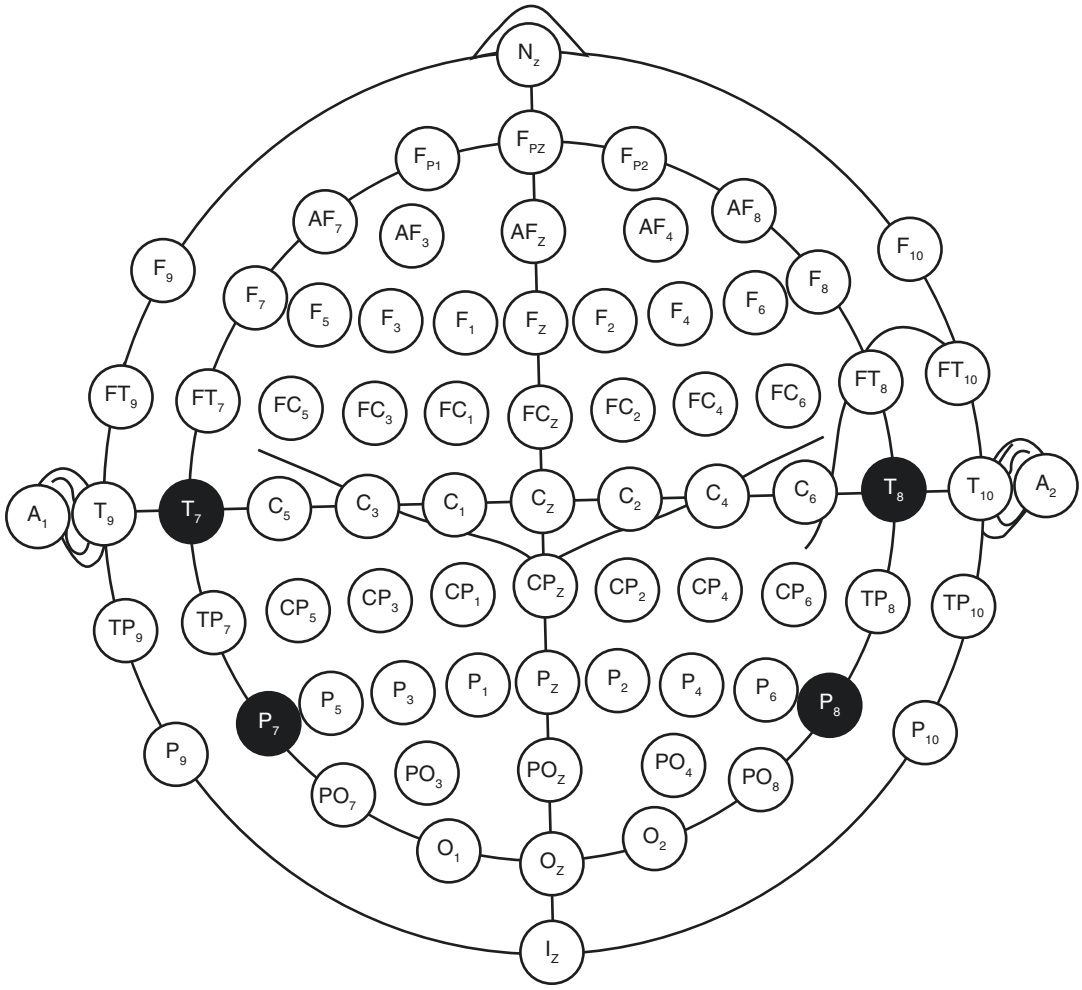

Fig. 10.7 Nomenclature for the 10–10 system

Table 10.2 Anteroposterior (AP) bipolar montage for recording EEG

Left	Right
Fp1–F3	Fp2–F4
F3–C3	F4–C4
C3–P3	C4–P4
P3–O1	P4–O2
Fp1–F7	Fp2–F8
F7–T3	F8–T4
T3–T5	T4–T6
T5–O1	T6–O2

Table 10.3 Referential montage using the ipsilateral earlobes as the reference

Left	Right
Fp1–A1	Fp2–A2
F3–A1	F4–A2
C3–A1	C4–A2
P3–A1	P4–A2
O1–A1	O2–A2
F7–A1	F8–A2
T3–A1	T4–A2
T5–A1	T6–A2

the mastoid process, the nose, the chin, the Cz electrode, and the base of the neck. An example referential montage is shown in Table 10.3.

A bipolar montage has an advantage of greater specificity than a referential montage since the electrode pair lies closer together. Referential montages may provide more sensitivity but are

less specific. The need to localize a change would make a bipolar recording preferred. If sufficient number of channels is used, these montages can also be quite sensitive.

The number of channels needed is dependent on the purpose of the EEG. The more channels recorded, the greater both the sensitivity and specificity of the EEG will be. For intraoperative monitoring, amplifier space and time are factors that may limit the number of recorded channels. Most IOM practitioners will use a minimum of eight channels for intraoperative EEG.

Recording Parameters

Filters

Filters can be used to accentuate EEG activity, but when used improperly can greatly attenuate EEG waveforms. Filters remove waves according to rigid mathematical rules and cannot discriminate EEG waveforms from artifact. Filters are discussed more completely in another chapter of this book. The use of analog filters changes the raw data prior to digitization and display and cannot be undone. In addition to the loss of data, aggressive use of analog filters may cause phase shifts in the data. These artificial alterations in the raw EEG data are best avoided with careful use of analog filters. When selecting analog filters for any bioelectric recording, it is important to know the frequency characteristics of the signal of interest. For intraoperative EEG, we generally desire a pass band between 0.5 and 70 Hz. These filter settings will allow the desired signal while minimizing high-frequency artifact. A notch filter may be used to eliminate 60-cycle noise as most of our EEG signal will fall at frequencies much lower than this. Unlike evoked potential recordings, where ringing artifact may occur with the use of a notch filter, the EEG is a passive recording and does not introduce the risk of a ringing artifact with notch filter use.

Display Parameters

Historically analog EEG was performed with a roll of paper moving under a series of pens (one for each channel) that would deflect proportionally to the recorded voltage output of the amplifier. The paper speed could be adjusted to change the display property of the EEG with slower paper speeds used to distinguish asymmetric slowing. By convention, the EEG time base is defined as the paper speed in millimeters or centimeters per second. Some modern intraoperative monitoring equipment, however, uses the same convention for EEG display as for evoked potentials, which is milliseconds/division. A division is generally 1 cm for most equipment and there are usually ten divisions in the test window. A good starting point for intraoperative EEG is 1000 ms/div which gives a 10-s sample of data in the window. The display sensitivity for voltage should initially be set near 70 μV/division. These parameters can be adjusted out of clinical necessity or personal preference.

Normal EEG Patterns

Analysis of EEG waveforms includes voltage, frequency, morphology, and topography.

EEG is a mixture of frequencies that vary greatly during infancy and childhood and again in the elderly. Normal EEG has an anteroposterior gradient characterized anteriorly by waves of lower voltage and higher frequency and posteriorly by waves of higher voltage and lower frequency.

The five (with the introduction of gamma) EEG frequencies are as follows:

- Delta: less than 4 Hz
- Theta: 4–7 Hz
- Alpha: 8–13 Hz
- Beta: 13–35 Hz
- Gamma: 35 Hz and above

Delta activity is normal in preterm neonates and in deep sleep (Fig. 10.8). Persistent

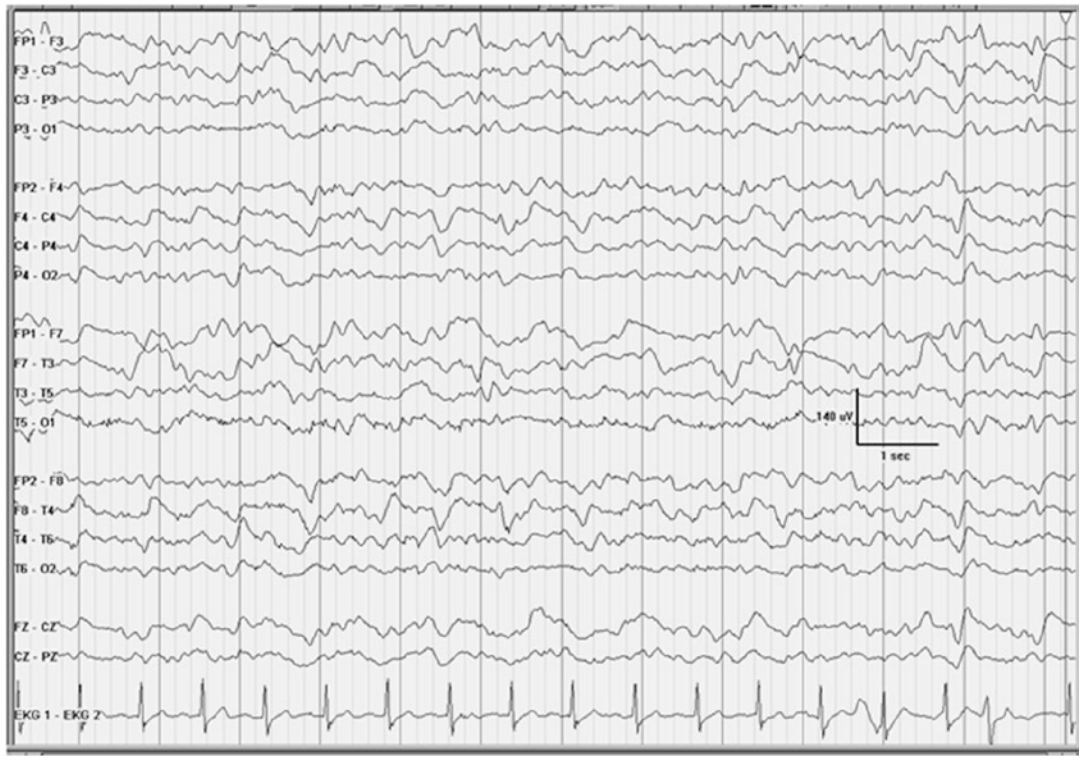

Fig. 10.8 Diffuse underlying delta activity with faster theta frequencies superimposed. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

delta activity without theta or alpha activity is abnormal if seen during wakefulness at any age [9]. Theta activity is enhanced by drowsiness and sleep (Fig. 10.9). There is great individual variation in the waveform, frequency, and amplitude of frontal and frontocentral theta seen in children and adults. The normal posterior dominant rhythm in adults is in the alpha frequency and is 8.5–11 Hz. The posterior dominant alpha rhythm is seen bilaterally over the posterior head region and attenuates with eye opening (Fig. 10.10). Beta activity increases with drowsiness, light sleep, and mental activation (Fig. 10.11). Sedative, hypnotic, and anxiolytic drugs, such as benzodiazepines and barbiturates, are potent activators of beta especially in the frontal and central regions. Gamma activity may be associated with conscious perception and attention processing [10] (Fig. 10.12).

Abnormal EEG Patterns

Abnormal EEG patterns are nonspecific for etiology. Abnormal activity can be focal, bilaterally diffuse, and unilateral or lateralized.

Abnormal EEG can either be any of the following:

1. Slowing of the background rhythm
2. Appearance of slow waves—arrhythmic delta activity (polymorphic delta) or intermittent rhythmic delta (monomorphic delta with a stereotyped waveform)
3. Paroxysmal activity—discharges of abrupt onset and sudden termination that are clearly distinguishable from the ongoing background
4. Specific patterns—burst suppression, periodic lateralized epileptiform discharges, triphasic waves, and generalized periodic epileptiform discharges

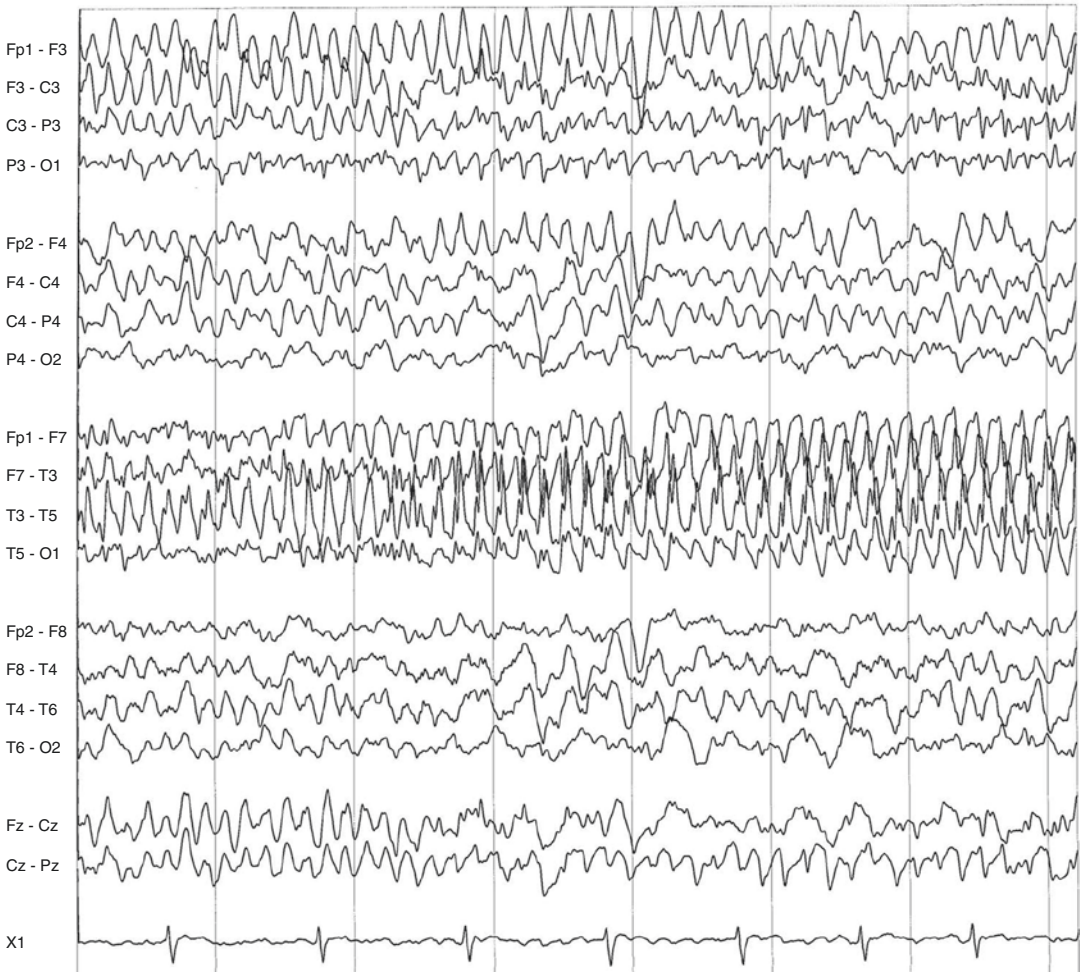

Fig. 10.9 Rhythmic theta activity seen in the left hemisphere signaling the onset of a seizure. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

Focal EEG abnormalities provide electrographic evidence of localized, abnormal cerebral function that is nonspecific for the etiology and may be seen with many different underlying lesions of the brain (Fig. 10.13). Some of the causes of focal EEG abnormalities include head trauma, tumor, stroke, intracranial hemorrhage, abscess, and herpes encephalitis.

Diffuse EEG abnormalities are also etiologically nonspecific. Diffuse slowing may have various morphologies and occur intermittently or continuously and reflect abnormal cerebral function. Diffuse slowing suggests a bilateral disturbance of cerebral function and represents an encephalopathy that is nonspecific for etiology. The most common causes of diffuse slowing are toxic, metabolic, infectious, or systemic disturbances, although severe diffuse lesions affecting the brain can produce diffuse slowing. Traumatic brain injury, coma, post-seizure state, advanced neurodegenerative diseases, ischemia, and even anesthesia can cause diffuse slowing.

Epileptiform discharges are distinctive waves or complexes, distinguished from background activity, and resembling those recorded in a proportion of human subjects suffering from epileptic disorders and in animals rendered epileptic experimentally [11]. Epileptiform patterns include spikes and sharp waves, with or without accompanying slow waves, which occur singly

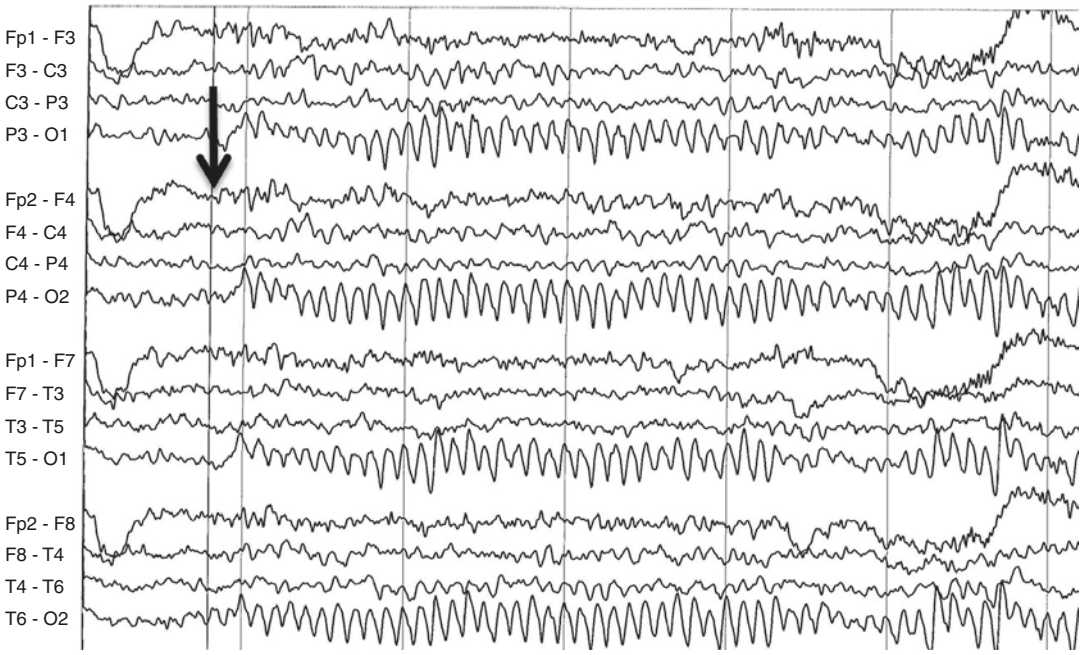

Fig. 10.10 Alpha activity attenuates or blocks (*closed arrow*) with eye opening. Alpha activity returns with eye closure (*open arrow*). Time between *solid vertical lines* = 1 s. Sensitivity = 7 μV/mm. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

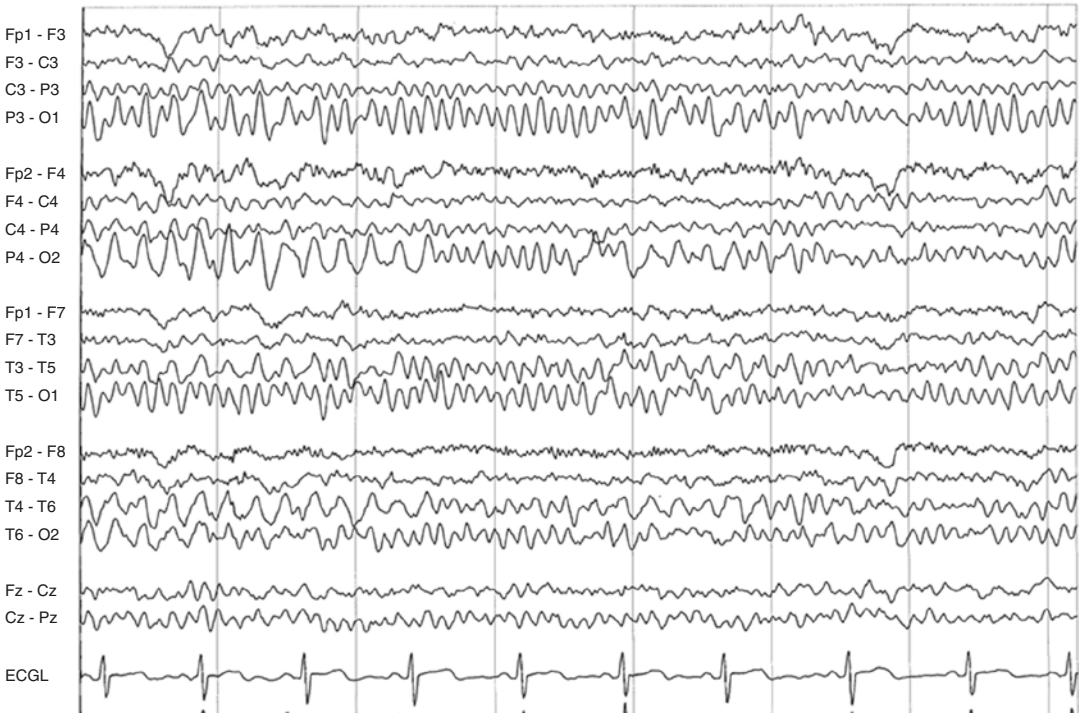

Fig. 10.11 Bifrontal beta activity; *oval* indicates an example. Time between *solid vertical lines* = 1 s. Sensitivity = 10 μV/mm. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

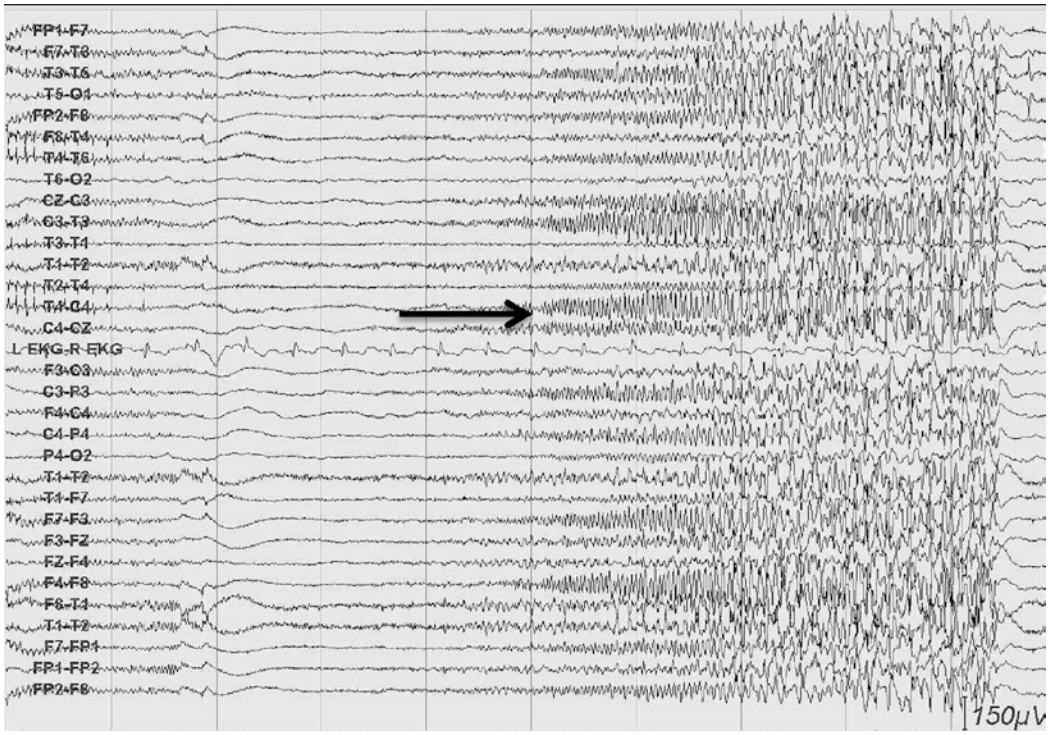

Fig. 10.12 Gamma activity seen at the onset of a seizure (*arrow*). Time between *solid vertical lines* = 1 s. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

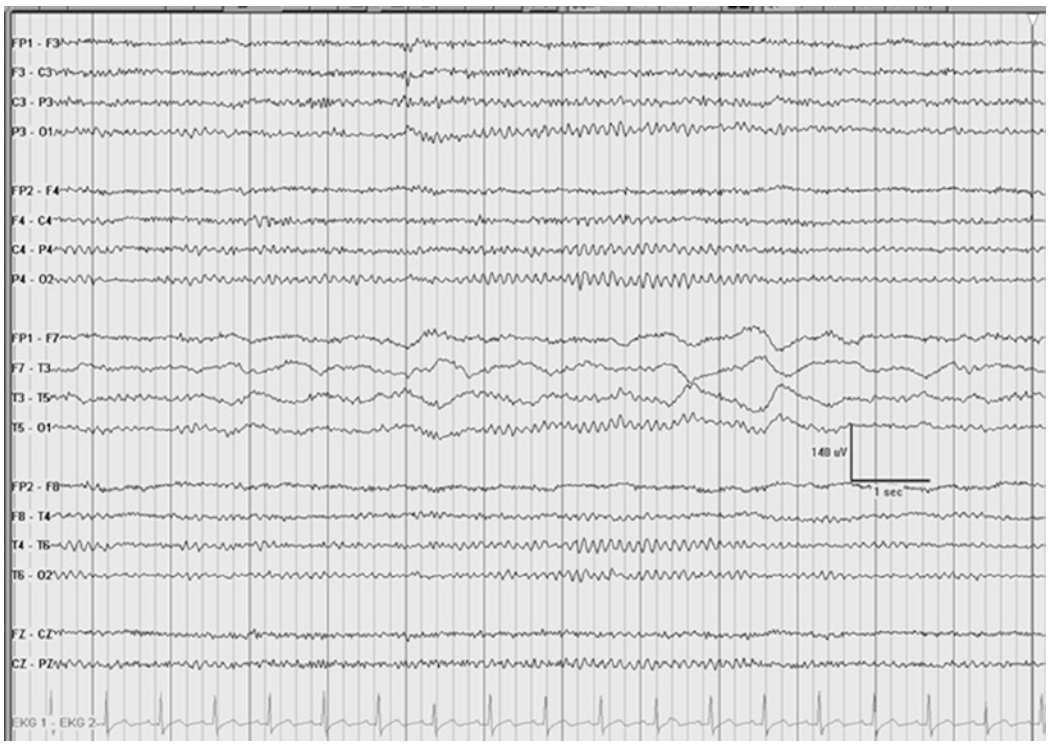

Fig. 10.13 Focal left temporal delta. Normal alpha rhythm is seen in both left and right occipital regions. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

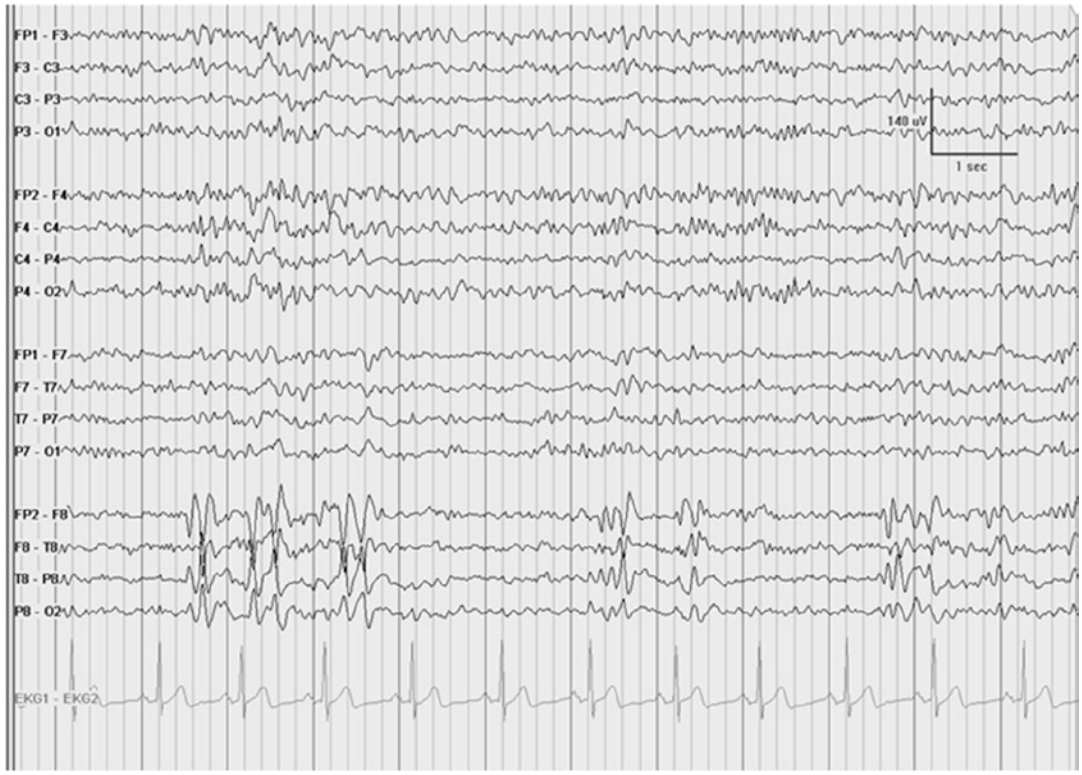

Fig. 10.14 Right temporal sharp waves occurring during sleep. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

or in bursts (Fig. 10.14). Spikes have a duration of 20–70 ms. Sharp waves have a duration of 70–200 ms. Epileptiform activity does not equate a diagnosis of epilepsy [12].

Spectral Analysis

The analysis of raw EEG patterns can be difficult, so most IOM machines offer a visual display of EEG called spectral analysis. IOM computers utilize mathematical algorithms to average 2–8 s of EEG raw data frequencies and plot frequency versus power to provide amplitude data over time. The spectral analysis provides a visual representation of the progression of EEG frequencies during the monitoring period.

The most common IOM-related EEG spectral analysis displays are Compressed Spectral Array (CSA) and Density Spectral Array (DSA). CSA utilizes a waterfall mountain range visual representation plotting frequency versus power (amplitude) of a given time period (Fig. 10.15). Each line of CSA represents average frequency of 2–8 s of raw EEG data. Each EEG montage receives its own plotting of CSA. In a simplified effort to view the trending of the CSA frequencies, a Power Spectral Edge (PSE) is applied vertically to the data and presents the area of 95–97% of the most represented frequency observed in those 2–8 s. Additionally, the PSE will display the current dominate frequency being tracked within the CSA montages window. DSA is similar to CSA; however, this display utilizes color to show the power of frequency ranges. Much like CSA, DSA has a vertical line tracking the dominant frequency within the averaged EEG time sample.

Spectral analysis provides the technologist the ability to view trending in raw EEG frequency of the course of monitoring. Trending of EEG frequency to the left suggests slowing while trends to the right suggests increases in frequency.

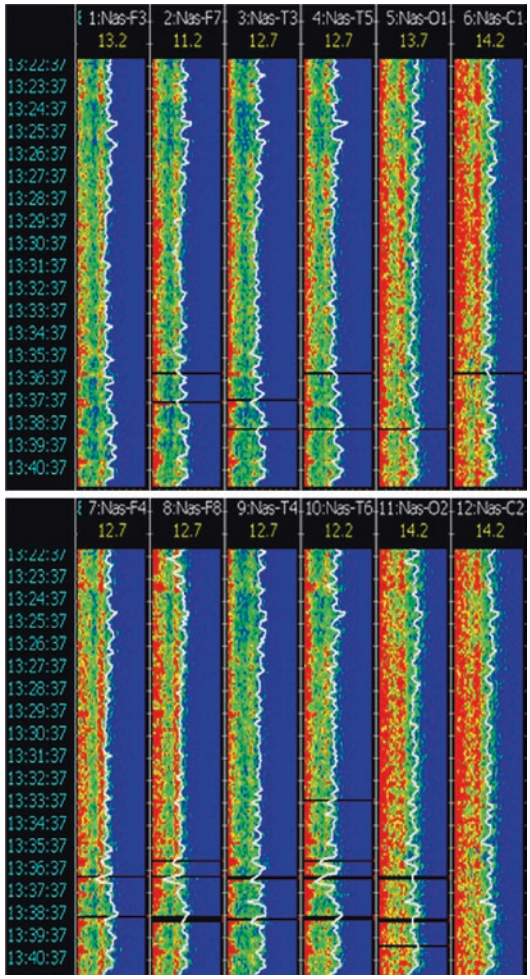

Fig. 10.15 Digital spectral array obtained during IOM for carotid endarterectomy surgery. The data are presented with the earliest traces at the top (beginning at time 13:27) and later traces below. Each column represents a recording channel with left hemisphere recordings in the top columns and right hemisphere recordings in the bottom columns. The white line connecting the traces in each column is the spectral edge (set to 97%). This means that 97% of all power in the EEG recording are comprised of frequencies to the left of the spectral edge. Watching for changes in the spectral edge can help identify slowing (or quickening) of the overall EEG pattern correlated with time and therefore surgical events

Correlating raw EEG and CSA/DSA to surgical events can provide useful insight into the status of cerebral function.

Anesthesia Effects

EEG recorded from the anesthetized patient is very different than EEG from the awake patient recorded in the neurology clinic. General anesthesia results in generalized slowing of the EEG pattern and the IOM clinician must be aware of these effects when establishing baseline criteria from which to compare all intraoperative data. While preinduction baselines can illuminate asymmetries in the EEG that will need to be documented, baselines taken during this time are not adequate for monitoring for intraoperative changes. A post-induction baseline is required and is the only baseline that intraoperative data should be compared to.

Burst Suppression

Burst suppression is an EEG pattern seen with pathology or as a result of general anesthesia. It is characterized by periods of low-voltage (nearly isoelectric) activity punctuated with brief bursts of activity (Fig. 10.16). Monitoring EEG for cerebral ischemia is not possible when the EEG is in a burst suppression pattern due to the large periods of electrical silence. For some procedures, a burst suppression pattern is induced intentionally as a mechanism of cerebral protection. The burst suppression pattern is characteristic of a metabolic state that requires less oxygen and therefore less blood. A burst suppression ratio of 1:4 is defined as 1 s of bursting for every 4 s of isoelectricity. This is the ratio demonstrated to be the most cerebroprotective. The IOM clinician is often called upon to monitor for adequate burst suppression and to work with the anesthesia team to deliver more drugs if cerebral activity begins to increase. Barbiturates such as thiopental are most often used to induce burst suppression. Propofol is another agent that is frequently used for this reason. When EEG cannot be a reliable indicator of cerebral ischemia because of the burst suppression pattern, the IOM clinician can rely on the cortically generated SSEP, which is still monitorable.

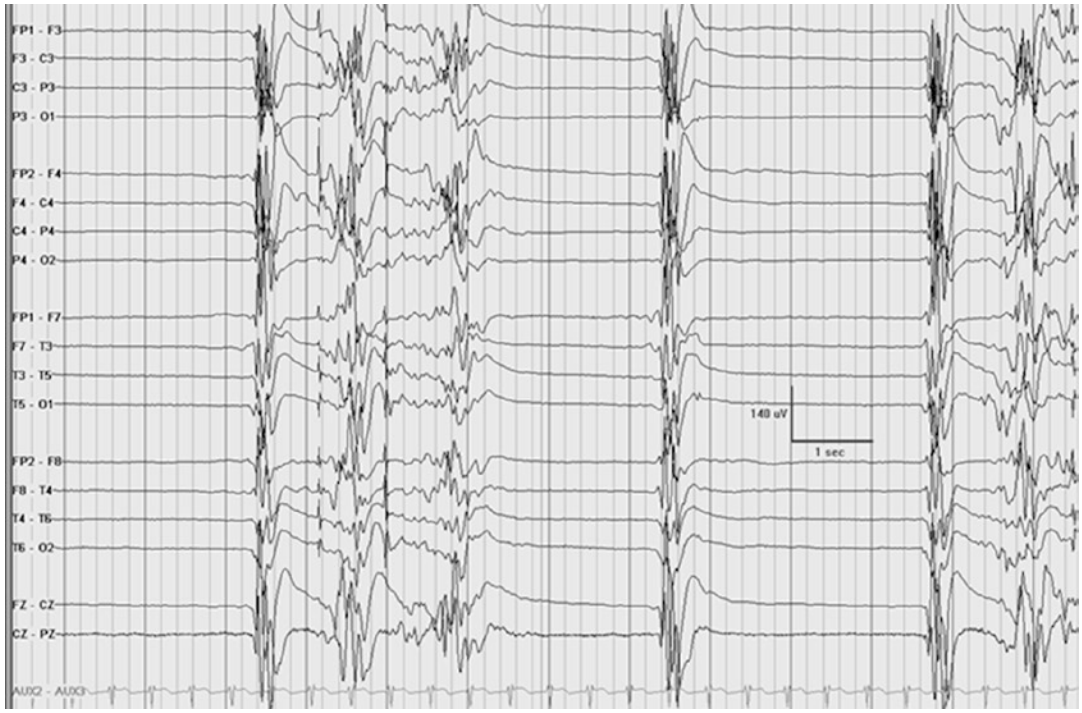

Fig. 10.16 Burst suppression. (EEG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

Use of EEG in IOM

The most common use of EEG during surgery is to monitor the adequacy of cerebral perfusion during procedures that may reduce blood flow to the brain such as carotid endarterectomy. As discussed above, monitoring for adequate burst suppression ratio is indicated for certain procedures such as cerebral aneurysm clipping or coiling. Intracranial EEG may be used to help identify the eloquent cortex and is briefly discussed below.

Intraoperative EEG may also be useful in determining the depth of anesthesia. Commercial devices that apply a proprietary algorithm to a two-channel frontal EEG are used by anesthesiologists to monitor anesthetic depth. This method is less reliable than a multichannel raw EEG used for the same purpose and is marketed to clinical personnel without sufficient EEG experience to interpret the raw data.

Electrocorticography

Intracranial EEG also called electrocorticography is used generally for mapping functional brain areas or defining epileptogenic foci. ECoG recordings from surgical implanted intracranial electrodes have direct contact with the neural tissue (Fig. 10.17). This technique has greater spatial resolution, sensitivity, and overall signal quality when compared to scalp EEG. By eliminating electrical resistors such as the dura, skull, and scalp, ECoG allows recording of faster frequencies and elimination of artifacts generated by scalp muscles and eye movements.

Conclusion

The use of EEG whether for diagnostic purposes in the clinic or for monitoring purposes in the operating room has had a huge impact on the

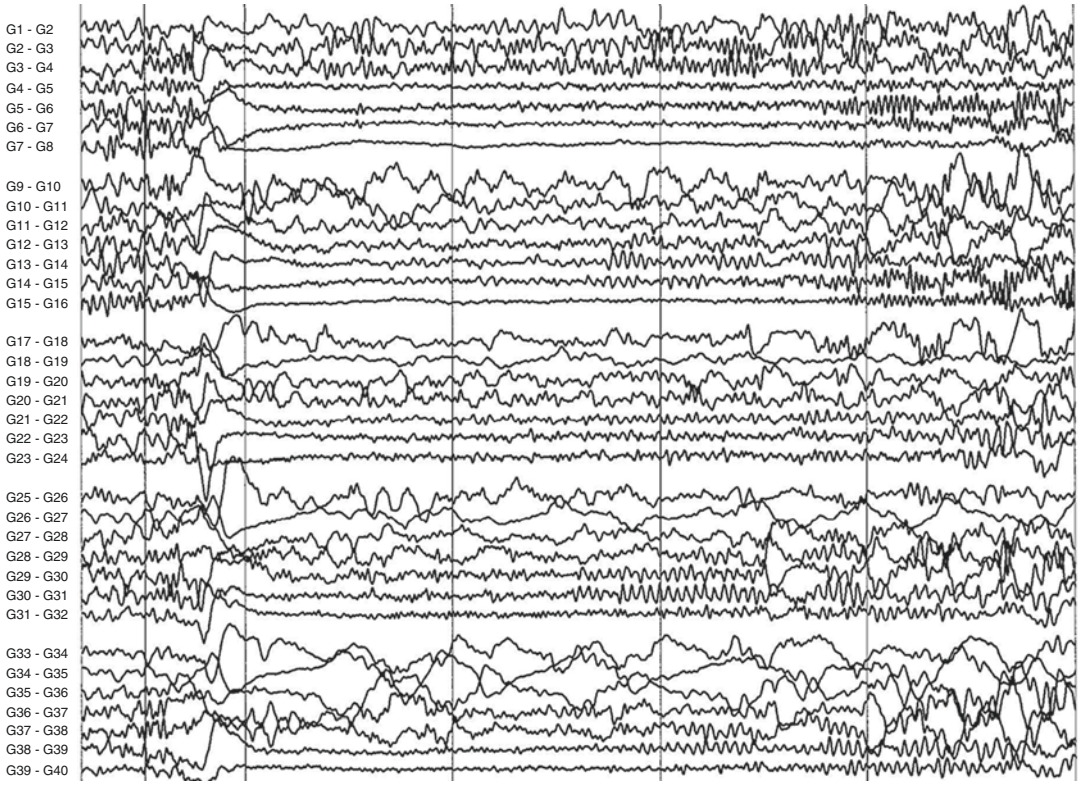

Fig. 10.17 Electrocorticogram (ECoG) recorded from a subdural grid. (ECoG epoch reprinted with permission of ASET—The Neurodiagnostic Society)

lives of patients. Electrophysiological recordings, such as EEG, provide real-time functional information about the patient's nervous system that cannot be achieved with even the best imaging techniques at this time.

Review Questions

1. What is burst suppression and how do you determine the adequacy of burst suppression for cerebral protection?
2. When should baseline intraoperative EEG be recorded? Why?
3. What are important considerations when selecting filters for EEG recording?
4. What is a dipole? Describe the importance of this concept in EEG recording.
5. What are the advantages and disadvantages of bipolar versus referential recording montages?

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The H-Reflex and F-Response

11

Jeremy Andrew Bamford and Scott Francis Davis

Introduction

Common electrophysiological recording modalities applied in the surgical setting include somatosensory evoked potentials (SSEPs), motor evoked potentials (TcMEPs), and electromyography (EMG). Central function is traditionally monitored with SSEPs and TcMEPs. Spinal nerve and nerve root function can be more easily assessed with EMG. While generally accepted to provide complete spinal cord protection, SSEPs are specific for the dorsal white matter tracts and the vascular territory of the posterior spinal arteries. The TcMEP is specific for monitoring descending white matter pathways of the lateral and anterior columns, but is also distinct in being the only routinely applied modality to monitor the integrity of the spinal gray matter. While useful in detecting gross changes in motor function as a result of spinal cord injury, TcMEPs do not monitor more complex spinal circuits including multisegmental, interneuronal, and propriospinal circuitry responsible for the control of voluntary movement. Furthermore, TcMEP monitoring has some contraindications and typically causes considerable patient movement and the risk of bite injury. Two other modalities, the Hoffmann reflex (H-reflex) and the F-response, have been proposed as valuable adjuncts to SSEPs and TcMEPs for monitoring spinal cord integrity during neurosurgical spine procedures [1].

The eponymously named Hoffmann reflex (H-reflex) is an electrical analogue of the tendon tap reflex. The H-reflex was first described in the early 1900s by Piper [2] and then further elaborated by Hoffmann [3], who described a long-latency muscular contraction in the triceps surae muscle in response to submaximal electrical stimulation of the posterior tibial nerve. The reflex was further studied in a series of papers in the 1950s by Magladery and colleagues, who first named this response for Paul Hoffman [4]. The H-reflex is still used in laboratory settings to assess neuronal organization and to interrogate the plasticity of spinal cord circuitry and in clinical practice to assess spinal reflexes, peripheral conduction velocity, and spasticity [5, 6].

Physiology of the Stretch and H-Reflex

The H-reflex is an electrically evoked response that operates via the same neuronal circuitry as stretch reflexes. In order to understand H-reflexes, it is best to review the basic physiology and

J. A. Bamford
Department of Anesthesiology, Louisiana State, University Health Sciences Center, New Orleans, LA, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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anatomy of the standard monosynaptic stretch reflex (Fig. 11.1a). Monosynaptic stretch reflexes, sometimes referred to as deep tendon reflexes, are evoked by clinicians during standard reflex testing and can be generated at multiple points on the body by performing a tendon tap with a small rubber mallet. When the muscle is stretched via a tendon tap, stretch-responsive sensory neurons termed Ia afferents are activated. The cell bodies of these Ia afferent neurons are located in the dorsal root ganglion. The central process of these neurons sends a collateral that terminates on

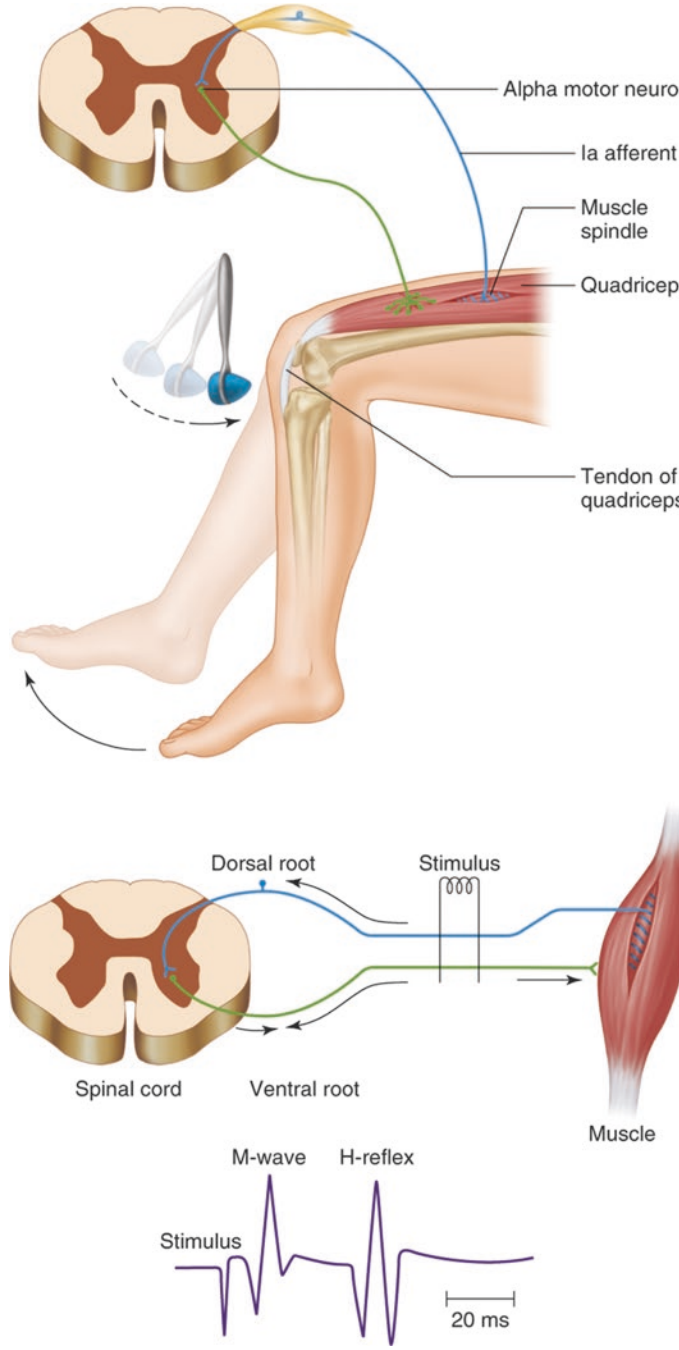

Fig. 11.1 The monosynaptic stretch reflex. (**a**) In response to rapid stretch, sensory Ia afferents activate alpha motoneurons in the ventral horns of the spinal cord, resulting in a delayed contraction of the muscle that was stretched. Clinicians make use of this response to test spinal cord reflexes. (**b**) The same pathways can be assessed intraoperatively using the H-reflex. A peripheral nerve is electrically stimulated, producing two responses that can be recorded with EMG. An early response, known as the M-wave, is elicited by direct activation of the muscle via motor axons. A later response, the H-reflex, is the result of activation of sensory Ia afferents, similar to what occurs when the muscle is stretched

alpha motor neurons in the ventral horn of the spinal cord gray matter. This synapse evokes a delayed contraction in the muscle from which the tendon reflex was initiated. The presence of a delayed muscular contraction in response to tendon tap as well as the latency of the muscular response can be evaluated in order to confirm the integrity of spinal cord reflexes. From a gross clinical perspective, the reflex is considered normal if an involuntary muscle contraction is observed after a slight delay following the tendon tap. The noticeable delay, or latency of the response, is a result of the fact that the signal must travel along sensory axons toward the spinal cord, synapse in the spinal cord, and then travel along motor axons back to the muscle before finally evoking a muscular response.

Electrically Evoked Responses

Unlike the stretch reflex that is detected by visual observation, EMG is used to record the M-wave, H-reflex, and F-response. In EMG testing, muscle contractions are recorded as compound muscle action potentials (CMAPs). Electrophysiological recordings afford the clinical scientist the opportunity to make precise measurements of latency, amplitude, and morphology (Fig. 11.1b).

Two physiological differences distinguish the H-reflex from the stretch reflex: (1) the H-reflex is evoked by electrical stimulation of a mixed motor and sensory nerve rather than by muscular stretch and (2) the H-reflex is activated proximal to the muscle and avoids entirely the muscle spindle fibers which, along with gamma motor neurons, play a role in modulating stretch-reflex gain. These factors make the H-reflex well suited to assessing spinal cord excitability [7].

The H-Reflex

Electrical activation of a mixed peripheral nerve creates an action potential that propagates in both directions along both sensory and motor axons (i.e., both ortho- and antidromically in afferent and efferent axons). The stimulation threshold for the H-reflex is typically low, and the reflex response is characterized by consistent latency between trials and simple morphology, leading to the conclusion that the reflex is mediated by large-diameter, monosynaptic Ia afferent fibers [5]. Despite this, there is some evidence for oligosynaptic components to the H-reflex response [6].

In humans, the CMAP response evoked by the lowest intensity stimulation is likely to be the H-reflex. The stimulus intensity where the H-reflex is first recorded is near or below the motor threshold, and therefore, an orthodromic motor response (M-wave) may not be recorded.

The H-reflex response is most like the muscle stretch reflex as it is evoked by the same process whereby a signal travels orthodromically along Ia sensory afferents toward the spinal cord, crosses the synapse onto alpha motor neurons, and then travels orthodromically along efferent motor axons to the muscle where it evokes a delayed muscular contraction [5]. Because of this similar route, it shares a similar characteristic delay with the stretch reflex. H-reflexes evoked at the popliteal fossa and recorded at the *soleus* muscle typically have a latency of ~30 ms, while those evoked at the cubital fossa and recorded at the *flexor carpi radialis* muscle have a latency of ~18 ms [8]. As with the stretch response, this delay is due to the longer route that this signal must take.

The M-Wave

As stimulation intensity is gradually increased, a shorter latency CMAP begins to appear in the recording. This response is termed the M-wave and is activated not through a reflex circuit but via the direct orthodromic transmission of an action potential along the motor axon to the neuromuscular junction. The stimulus intensity where the M-wave is first recorded is the termed the motor threshold. The M-wave response has the shortest latency because it is the simplest physiologically, being the result of the direct activation of the motor axon and subsequent transmission of an action potential to the neuromuscular junction, producing a contraction of the

postsynaptic muscle. As stimulus intensity increases further, the H-reflex will peak in amplitude and then begin to decline as the M-wave increases. Near supramaximal stimulation intensities, the M-wave dominates the recording as its amplitude peaks and the H-reflex disappears altogether.

The F-Response

By the time stimulus intensity becomes supramaximal, a third CMAP response appears on the EMG recording with a similar latency to the H-reflex. Termed the F-response, this response is not a reflex but is generated by an action potential that travels first antidromically and then orthodromically along motor axons. As just explained, the initial orthodromic action potential generated by electrical stimulation will generate a short-latency response, the M-wave. However, the same motor axons will also generate antidromic action potentials that travel toward the spinal cord along the same axons. When the antidromic action potential reaches the motor neuronal pools, the majority of these action potentials will be abolished. However, some of these signals will survive to depolarize the cell body causing an orthodromic action potential to form and travel back down the same motor axons. This "backfiring" of the motor neuron results in a CMAP response in the EMG recording. The population of motor units recruited to produce an F-response will vary from trial to trial yielding variable amplitude, latency, and morphology. This is one way in which the F-response can be distinguished from the H-reflex [9].

Ordered Responses Explained

The H-reflex, M-wave, and F-response are recruited in an ordered manner by electrical stimulation of increasing intensity. This occurs because the excitability of axons when evoked by electrical current is directly related to their diameter and input resistance; the largest axons will be recruited by the lowest stimulus intensity [10]. The largest diameter axons in a mixed peripheral nerve are the Ia afferent axons responsible for carrying the sensory action potential which initiates the H-reflex. The second largest group of axons are those of the alpha motor neurons, especially those that innervate larger, fast-twitch fatigable motor units in skeletal muscle. There is some overlap in the diameters of these axons, which explains why there is also some overlap in the intensities at which the M-wave and H-reflex are recorded. Nevertheless, the H-reflex is typically first noted at stimulus intensities that are subthreshold for the M-wave.

Advantages of the H-Reflex

Because H-reflexes are single-sweep and do not require averaging they offer a real-time test, similar in this respect to TcMEPs. They are also like TcMEPs in that they involve spinal cord circuitry in the gray matter; however, unlike TcMEPs they can be run without having to pause or interrupt the surgery as they produce little or no detectable movement. Furthermore, they have been shown to be stable with anesthetic regimens commonly employed to allow intraoperative monitoring [11].

Perhaps the greatest physiological advantage of H-reflexes is that they can be used to assess not just the nerve roots through which the afferent and efferent signal travels but complex suprasegmental, propriospinal, and interneuronal circuitry that affects the reflex arc both pre- and postsynaptically [6]. When evoked by stimulation of the posterior tibial nerve at the popliteal fossa, or the median nerve at the cubital fossa, H-reflexes can be minimally understood to be providing information about the integrity of S1 and C6/C7 nerves and nerve roots, respectively. However, the potential advantage of H-reflex monitoring is that it may provide a way of monitoring the integrity of a much larger network of suprasegmental spinal cord circuitry. Leppanen has speculated that the loss of H-reflexes following spinal cord trauma may have to do with uncoupling of the central pattern generator in humans and the disruption of inputs onto segmental afferents, yielding a change in reflex gain [8]. Although this is an

intriguing hypothesis, it is difficult to be certain about the specific mechanisms of H-reflex suppression in humans following spinal cord trauma.

Two reports using H-reflexes in the operating room have described H-reflexes as being remarkably sensitive to intraoperative events. Standard surgical maneuvers such as hammering with a mallet, distraction, and derotation of the spine resulted in transient decreases in H-reflex amplitude [12, 13]. This decrease in H-reflex amplitude was repeatedly observed across multiple procedures and was correlated with stressful spinal manipulations and perturbances of the spinal cord. The authors of this chapter have observed similar decreases in H-reflex amplitude correlated with spinal corrections or EMG bursts observed during posterior decompressions (Fig. 11.2). A more recent case study involving severe scoliosis correction reported loss of both TceMEP and H-reflex signals following a hypotensive event [14]. The physiological signals recovered following re-establishment of baseline mean arterial pressure.

Practical CONSIDERATIONS

Anesthesia

As with other intraoperative modalities, H-reflex and F-response data can be compromised by anesthetic regimens that are not optimized to provide the best environment for achieving valid neurophysiological results. Critically, H-reflexes and

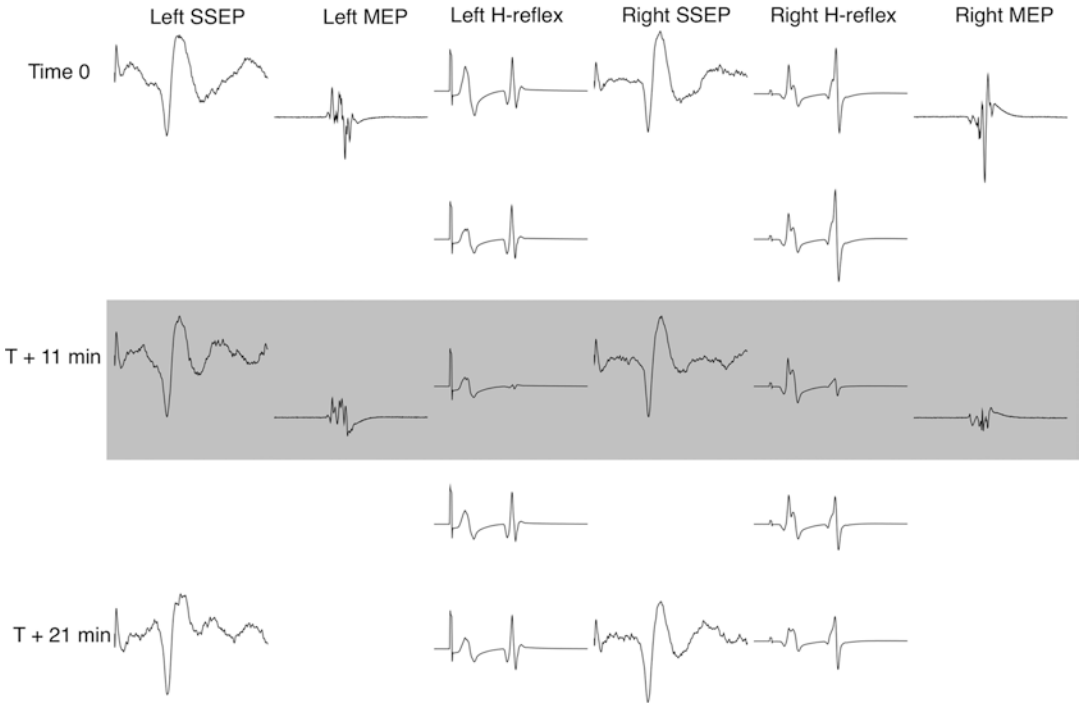

Fig. 11.2 The H-reflex is sensitive to spinal irritation. Displayed signals were gleaned during a complex scoliosis correction in an 18-year-old male. SSEP and H-reflex tests were gathered at regular intervals, while the TcMEP was run as often as practical, in communication with the surgical team. Pictured signals include bilateral cortical SSEPs evoked from the posterior tibial nerve, bilateral H-reflexes recorded at the *soleus* muscle, and bilateral TcMEPs recorded at the *abductor hallucis* muscle. During osteotomy, a large EMG burst (not shown) was observed across multiple lower limb muscles bilaterally in response to a distinct hammer strike upon the osteotome. The surgical team noted the same response as a brief but large patient spasm and requested TcMEPs to be tested. H-reflexes were significantly diminished for a period of approximately 5 min bilaterally. SSEPs remained undiminished while TcMEPs were diminished in amplitude but remained present in all recorded muscles bilaterally. Both H-reflexes and TcMEPs were determined to be unchanged from baselines at close and the patient awoke with no deficit

F-responses rely upon accurate recordings of muscular contraction via EMG. As such, they are strongly affected by paralytics applied during surgery. Neuromuscular blocking agents will diminish or even abolish the CMAP responses evoked as H-reflexes or F-responses. Interpretation of H-reflexes and F-responses should take into account the degree of neuromuscular blockade.

H-reflexes are modified by complex multisegmental, propriospinal, and interneuronal spinal networks [6]. Commonly applied anesthetics can alter the excitability of these networks, potentially yielding invalid results. H-reflex and F-response amplitudes are diminished significantly by the use of inhalants such as isoflurane and nitrous oxide [15]. Furthermore, H-reflex amplitudes show a concentration-dependent suppression in response to sevoflurane or propofol anesthesia [16, 17]. The same authors argue that both propofol and sevoflurane cause an increase of presynaptic Ia inhibition, a likely cause of H-reflex suppression [18, 19].

Previous authors have made suggestions regarding the limits of various anesthetic regimes whereby H-reflexes and F-responses are likely to remain valid [8]. The authors of this chapter can attest that H-reflexes and F-responses can be readily evoked by most anesthetic regimens that are appropriate for EMG, SSEP, and TcMEP monitoring, including total intravenous anesthetic, a mixture of volatile inhalants and propofol/remifentanil, or the use of up to 1.0 MAC of volatile inhalants. Although H-reflexes and F-responses are suppressed by these regimens to one degree or another, the stability of the H-reflex with stable anesthetic conditions has been established [11].

Stimulation Characteristics

Intraoperative H-reflexes are primarily evoked from *soleus* and *flexor carpi radialis* muscles in response to popliteal fossa and cubital fossa stimulation, respectively (Fig. 11.3). Stimulation can be achieved using needles or pads in a bipolar configuration or by placing the cathode in the popliteal/cubital crease with the anode placed on the opposite side of the joint [20]. The authors of this chapter have had considerable success with the latter, cross-joint stimulation configuration and prefer it, although it typically requires a higher stimulus intensity to evoke a H-reflex. The H-reflex is optimally activated by single pulses with relative long stimulus pulse widths of 0.5–1.0 ms. The stimulus pulse is typically monophasic and relatively low intensity. Although the first H-reflex response can often be elicited at a stimulus intensity below 10 mA, it is difficult to prescribe a specific stimulus intensity due to variables related to the individual patient and the selection of needle or pad electrodes for stimulation. Nevertheless, it can be said that the stimulus intensity to elicit a maximal H-reflex response should be near or even below the motor threshold.

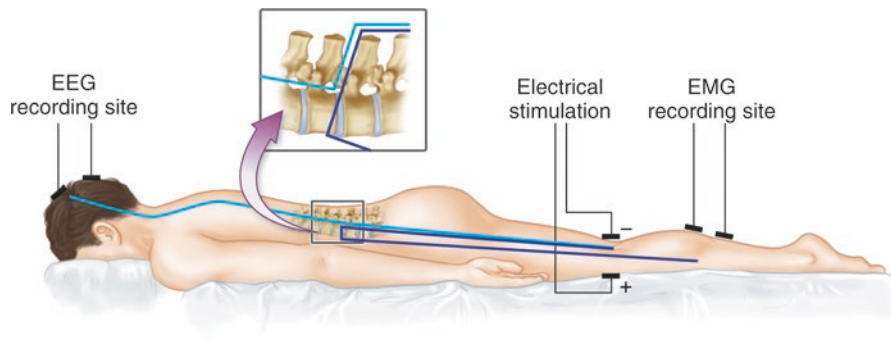

Fig. 11.3 Configuration of H-reflex testing. H-reflexes are most easily recorded from soleus muscle but can be recorded from multiple lower limb muscles in response to stimulation of the posterior tibial nerve at the popliteal fossa. Recording is typically bipolar at the soleus muscle. Stimulation can be bipolar at the popliteal fossa or monopolar across the joint as pictured above

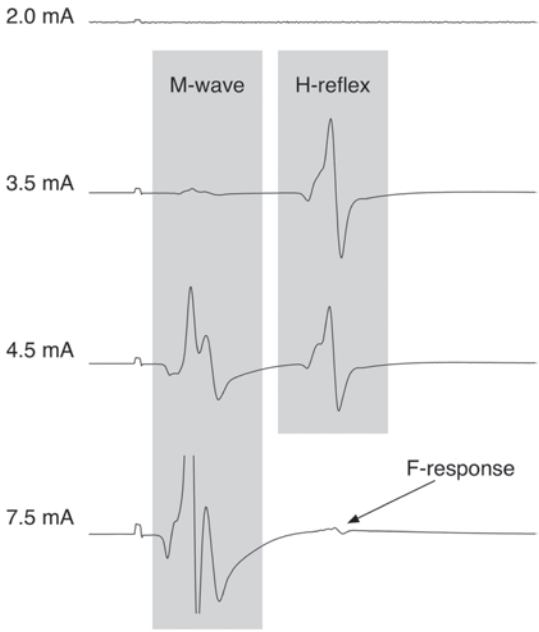

Fig. 11.4 Optimizing the H-reflex response. H-reflex amplitude will be affected by changing stimulus intensity. At low intensities the M-wave will be absent and a small H-reflex will appear. As stimulus intensity is gradually increased the H-reflex will peak in amplitude before declining as the M-wave comes to dominate the recording. F-responses can be noted at a similar latency to the now absent H-reflex

As stimulus intensity is increased, the H-reflex will reach maximal amplitude and then decline as the M-wave increases to its maximum (Fig. 11.4). Stimulus intensity should be chosen at the beginning of a procedure in order to maximize the H-reflex amplitude. Multiple H-reflex trials should be attempted in order to determine the stimulus intensity at which the H-reflex amplitude is maximized. Individual pulses should not be applied at intervals less than 1 pulse every 2.0 s (0.5 Hz stim rate). Some authors have even suggested that H-reflexes may be depressed by stimulating more often than once every 10 s [5, 21].

Recording Characteristics

In diagnostic or research settings, the soleus muscle is often selected for recording the lower limb H-reflex [7]. Commonly, one electrode is placed at the mid-calf, just distal to the bifurcation of the medial and lateral lobes of the *gastrocnemius* muscle. However, the medial gastrocnemius is also often targeted with bipolar needle electrodes over the medial aspect of the upper one-third of the calf [8]. We often use a referential EMG configuration with one needle over the *medial gastrocnemius* muscle and one over the *soleus* muscle. Recordings for the lower limb are single-sweep with a total sweep time of 50–100 ms. The medial gastrocnemius H-reflex response typically has a latency of ~30 ms, measured from the stimulus pulse onset, while the M-wave latency is closer to 15 ms or less. These numbers can vary with patient height or with conditions that affect peripheral conduction velocity. Since the M-wave, H-reflex, and F-response are recorded by EMG as CMAPs, the filter settings are similar to those used for free-running or triggered EMG. The high- and low-pass filters should be 3–30 Hz and 3–10 kHz, respectively. Notch filters to remove 60 Hz mains noise should generally be avoided.

Recognizing the H-Reflex

When reviewing an EMG recording for potential H-reflex responses, the neurophysiologist should keep in mind the characteristics of the H-reflex. The H-reflex response should be of appropriate latency as discussed above, have a short duration, simple morphology, high amplitude relative to the M-wave, and should be characterized by stability across multiple trials. After consideration of the latency and amplitude of the recorded CMAP, the M-wave should be immediately distinguishable from the H-reflex. In contrast, the F-response may be confused with the H-reflex due to their similar latencies. However, the F-response differs in a number of key ways. Firstly, the amplitude of the F-response is typically considerably less than that of the H-reflex. Secondly the F-response is less stable than the H-reflex with respect to latency, amplitude, and morphology. Finally, the amplitude of the corresponding M-wave CMAP recorded along with the F-response is much larger than that which

would typically be recorded with a H-reflex. This indicates supramaximal stimulation of the nerve, a condition that typically precludes the recording of H-reflexes. Other authors have noted that the H-reflex response at its peak will typically reach 50–100% of the M-wave amplitude [22].

Assessing the H-Reflex

While sometimes used intraoperatively, there are no universally accepted criteria for interpreting H-reflex data. In addition, only a handful of primary papers have been published containing intraoperative H-reflex data [11–13, 23, 24]. This makes the establishment of alarm criteria difficult. Factors that can be monitored for change include peak-to-peak amplitude, latency of the response, and the ratio of the maximal H-reflex to maximal M-wave amplitude [25]. Although these elements can all be monitored, no objective criteria have been described relating to what would constitute an alarming alteration of these values. Nevertheless, the H-reflex has been described as remarkably stable given stable anesthetic conditions [11, 12]. As such, the authors of this chapter recommend that H-reflexes be established at the beginning of a procedure and monitored for changes throughout the operation. Lacking any objective criteria, a decrease in amplitude of greater than 50% and an increase in latency of greater than 10% are reasonable and accepted criteria to use when deciding whether or not to communicate a change to the surgical staff. H-reflex changes correlating with changes of either SSEP or TcMEP are particularly alarming. Currently, the clinical utility of the F-response remains under investigation.

Troubleshooting the H-Reflex

As mentioned above, H-reflexes are recorded as an EMG response and are not recordable in the presence of neuromuscular blocking agents. Accordingly, a train-of-four test should be used to inform the neurophysiologist of the level of paralysis. If H-reflexes prove unobtainable at any point during the procedure, a train-of-four can eliminate neuromuscular blockade as a cause of signal loss.

It is not uncommon for the optimal stimulation intensity to vary during a surgical procedure. If the amplitude of the H-reflex or the maximal H-reflex to maximal M-wave ratio should decrease during the procedure, the first step should be to increase or decrease the stimulus intensity through multiple trials in order to optimize the H-reflex CMAP amplitude. The goal when testing H-reflexes should be to adjust the stimulus intensity to produce the maximal H-reflex response. The optimal stimulation intensity can drift by a few milliamps and may need to be retested. This could simply be due to a change in resistance of the stimulating electrodes.

Conclusion

The H-reflex is a useful tool for monitoring spinal cord excitability in the surgical suite. It can be run without disturbing the surgical staff, it does not require placing any electrodes beyond those commonly placed for more routine spinal cord monitoring modalities, and the response appears to be effected by anesthesia similarly to SSEP and TcMEP monitoring. Nevertheless, H-reflexes and F-responses are one of the least well-studied modalities applied intraoperatively. Unfortunately, only a handful of papers containing primary data exist. Moving forward, it will be necessary to further characterize these responses intraoperatively in order to continue to assess their value and to establish reliable alarm criteria for transmitting a warning to the surgical staff.

Review Questions

1. What are the characteristics allowing for recognition of the H-reflex recording in humans?
2. When is the physiological basis for the F-response?
3. What advantages might intraoperative H-reflex monitoring offer to the clinician?
4. At what thresholds are the M-wave, H-reflex, and F-response evoked?

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12 Monitoring Procedures of the Spine

Denise A. Birkholz and Scott Francis Davis

Introduction

The vertebral column is an extremely complex structure, and surgical procedures involving the cervical, thoracic, and lumbar levels pose a risk to the neural elements. Although the overall incidence of a major neurologic complication such as paraplegia is low, advances in intraoperative neurophysiological monitoring (IOM) techniques have made multimodality monitoring an effective approach for preventing iatrogenic injury to the nervous system during spinal surgery.

Mixed nerve somatosensory evoked potentials (SSEPs) and transcranial motor evoked potentials (Tc-MEPs) are the IOM modalities most often used to monitor the spinal cord. Upper limb SSEP monitoring can also help prevent peri-surgical complications such as ulnar neuropathy and brachial plexopathy. However, these modalities have not been proven highly sensitive to detecting spinal nerve root injury, although there is some evidence supporting the sensitivity of Tc-MEPs for impending nerve root injury. Therefore, the addition of electromyography (EMG) and triggered EMG can be used to monitor the spinal nerve roots.

D. A. Birkholz
Neuromonitoring Associates, LLC, Las Vegas, NV, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

Spinal Anatomy

The spine is composed of 33 interlocking bones, surrounded by ligaments and muscles, that provide the main support for the trunk and protect the spinal cord (Fig. 12.1). The 7 cervical, 12 thoracic, and 5 lumbar vertebrae are each separated by fibrocartilaginous discs that act as shock absorbers and allow the neck and back to move in multiple directions. Additionally, five fused vertebrae form the sacrum, and four coccygeal bones form the tailbone or coccyx.

Each vertebra has critical functional parts. The vertebral body is the weight-bearing portion of the vertebra and is located anterior to the vertebral canal. Posterior to the vertebral body are bony projections that form the vertebral arch: bilateral pedicles, lamina, transverse processes, and facet joints and a single posterior spinous process (Fig. 12.2). The vertebral canal contains the spinal cord or cauda equina, fat, ligaments, and blood vessels. Under each pedicle, spinal nerves exit the spinal cord and pass through the intervertebral foramen to branch out to the body. Surgeons often remove the lamina of the posterior vertebral arch to access and decompress the spinal cord or spinal nerves to treat spinal stenosis, tumors, or herniated discs.

The spinal cord extends from the foramen magnum to around spinal level L1. At L1, the terminal portion of the spinal cord is called the conus medullaris. From the conus, a bundle of

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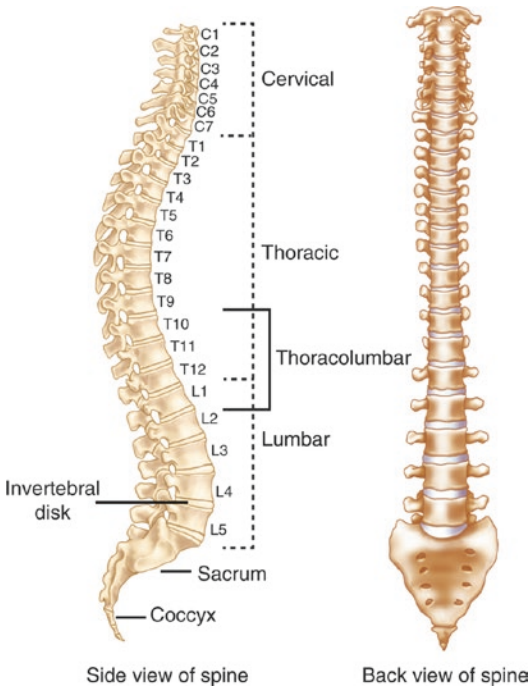

Fig. 12.1 Lateral view (left) and posterior view (right) of the spine. The cervical, thoracic, and lumbar vertebrae are separated by a cartilaginous disc that provides cushioning and allows for movement. The sacral and coccygeal vertebrae are already fused

spinal nerves called the cauda equina further extend down to their respective vertebral level where they exit the spinal column.

Thirty-one pairs of spinal nerves emerge from the spinal cord (Fig. 12.3). There are 8 cervical spinal nerves, 12 thoracic nerves, 5 lumbar nerves, 5 sacral nerves, and 1 coccygeal nerve. Each spinal nerve is composed of motor and sensory fibers that pass through an intervertebral foramen between adjacent vertebrae. Cervical and thoracic spinal nerve roots exit laterally from the vertebral canal between adjacent pedicles, while lumbosacral roots extend downward as part of the cauda equina before exiting through foramina below the spinal cord. Nerve roots can be injured during surgery by electrocautery, drilling, retraction, or misplaced hardware.

Procedures of the Cervical Spine

The main function of the cervical spine is to support the head and allow it to move. The first cervical vertebra (C1), sometimes called the atlas, is a bony ring (not a true vertebral body) that

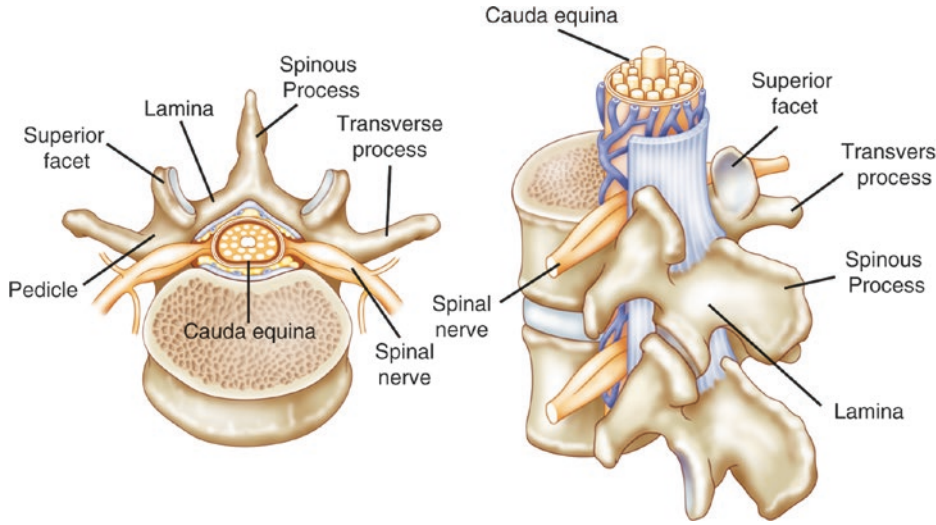

Fig. 12.2 Superior view of a vertebra showing the location of the critical functional parts relative to the spinal canal. The vertebral arch protects the spinal cord and exiting nerve roots and is formed from bilateral pedicles, lamina, transverse processes, and facet joints and a single posterior spinous process

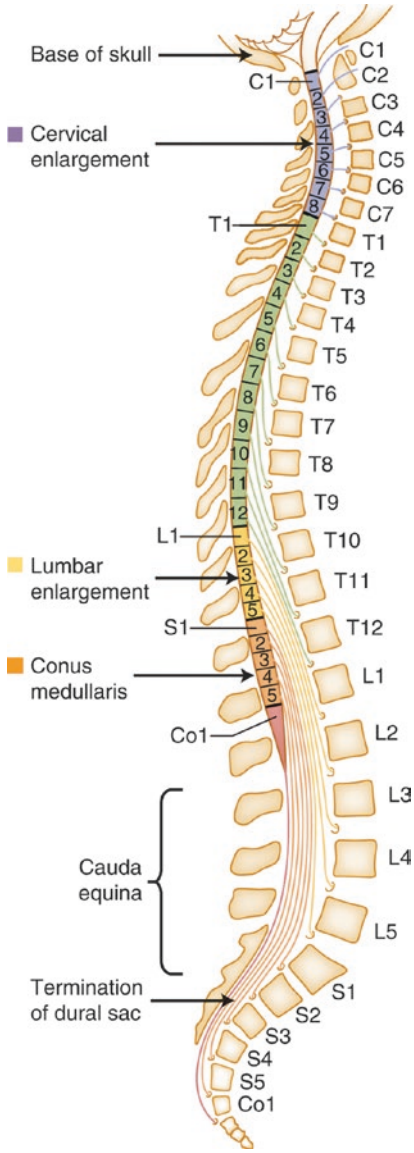

Fig. 12.3 Thirty-one pairs of spinal nerve roots branch off the spinal cord. Cervical and thoracic spinal nerve roots exit laterally from the spinal canal between adjacent pedicles, while lumbosacral roots extend downward as part of the cauda equina before exiting through foramina below the spinal cord

connects directly to the skull. Together with the C2 vertebra, or axis, these two vertebral joints attach the skull to the spine and allow for a range of movement in all directions. The remaining C3–C7 vertebrae form the lordotic curve of the neck. Also specific to the cervical vertebrae is the presence of transverse foramina that enclose and protect the vertebral arteries.

Cervical spine surgery is generally performed to treat nerve impingements (radiculopathy), spinal cord compression (myelopathy), or spinal instability that is causing pain and weakness. Common cervical procedures include anterior cervical discectomy and fusion (ACDF), posterior cervical fusion (PCF), and cervical corpectomy. Risks during surgery include but are not limited to cord contusion, motor loss or weakness, peripheral nerve injury, or vascular compromise.

Injury to the C5 nerve root is the most common injury from cervical surgery and can result in pain, paresis, or paralysis of the shoulder. Other nerve roots are subject to postoperative palsy, but most complications occur at C5 due to its shorter length and more obtuse angle of exit from the foramen [1, 2]. The C5 nerve root is the only nerve supply to the deltoid muscle of the shoulder, so injury to the nerve root leads to an obvious weakness of this muscle and difficulty raising the arm to the side [2]. The potential for C5 palsies can be detected by using EMG and Tc-MEP monitoring during spinal surgery with specific focus on the deltoid and biceps brachii muscles. Brachial plexopathy resulting from positional or traction-induced injury may mimic C5 palsy [3]. Many surgeons maintain downward traction on the shoulders during a cervical surgery. Injury to the brachial plexus may result from this traction and can be detected by monitoring SSEPs during the procedure.

Anterior Cervical Discectomy and Fusion

ACDF is a procedure often performed to remove a herniated or degenerative disc. Narrowing of the vertebral canal, a condition called spinal stenosis, can cause chronic pain, numbness, and muscle weakness in both upper and lower extremities. Bone spurs can also develop resulting in foraminal stenosis thus compressing the exiting spinal nerves.

The surgical approach during an ACDF is from the anterior, or front, of the neck. An anterior approach allows the surgeon access to the disc space without disturbing the spinal cord, spinal nerves, and posterior neck musculature. An incision is made and midline structures and musculature are retracted to expose the vertebral bodies and disc space. Bone and disc fragments are removed in order to decompress the spinal cord and nerve roots. After the disc space is cleaned out, an implant (often made of bone, metal or a biopolymer like PEEK) is placed between the vertebral bodies and secured with a metal plate and screws. The ultimate goal of the surgery is to create a bony fusion between the adjacent vertebrae with the metal hardware simply acting as a cast, stabilizing the spine until fusion occurs (Fig. 12.4).

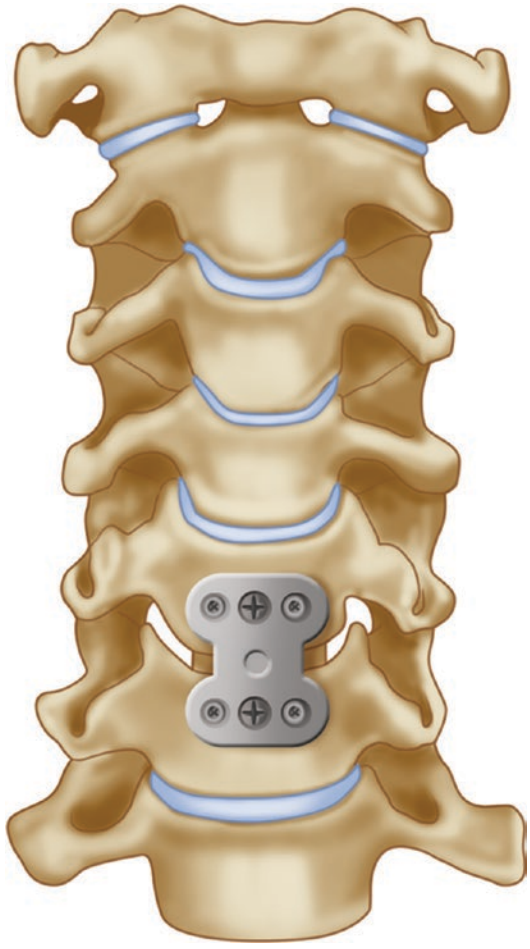

Fig. 12.4 Example of a metal plate and screws placed over the bone graft during ACDF surgery

A common complication in anterior cervical surgery is vocal cord paralysis resulting from an injury to the recurrent laryngeal nerve (RLN). Patients with RLN palsy may experience hoarseness, develop a cough, or lose their voice completely and it may take several months for the nerve to recover [4, 5]. EMG monitoring using a special endotracheal tube has been shown to be useful in detecting injury to the RLN. Monitoring the RLN is discussed in detail in Chap. 16 of this book.

Multimodality monitoring for anterior cervical fusions should include upper and lower SSEPs and Tc-MEPs to monitor spinal cord function, as well as EMG from the myotomes at risk to provide protection for the nerve roots. Positional injury may also be detected with upper extremity SSEP monitoring.

Posterior Cervical Fusion

If spinal stenosis cannot be relieved by an anterior approach, or if the patient's spine is not stable enough before or after an anterior approach, the surgeon may opt for a posterior cervical laminectomy and fusion (PCF). The object of this procedure is the decompression of the neural elements and stabilization of the cervical spine. Posterior fusions are also performed for instability of the cervical spine resulting from trauma or a degenerative pathology.

For PCF surgery, the patient is placed in a prone position (on their abdomen) with the head made immobile by placing it in a special frame called a Mayfield (Fig. 12.5). The head is held in the Mayfield with pins. After the incision is made in the back of the neck, the surgeon will then dissect down through the subcutaneous tissues to the fascia overlying the spinous processes. Retractors are inserted to hold the muscle away from the spine, and the surgeon will begin to remove the lamina and other bony elements in order to decompress the spinal cord and nerve roots.

Various types of instrumentation are used to posteriorly fuse the cervical spine. Wiring can be used to stabilize the upper cervical vertebral seg-

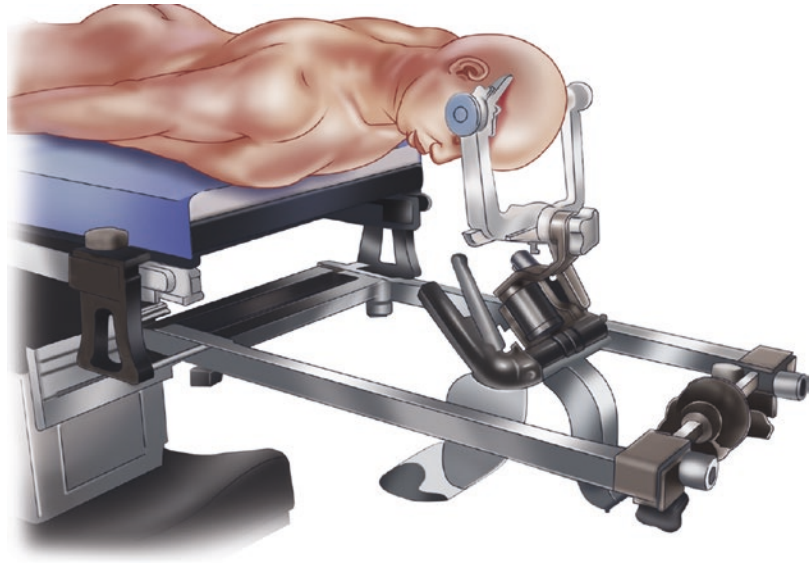

Fig. 12.5 Drawing of a patient positioned for a posterior cervical fusion using a Mayfield head frame

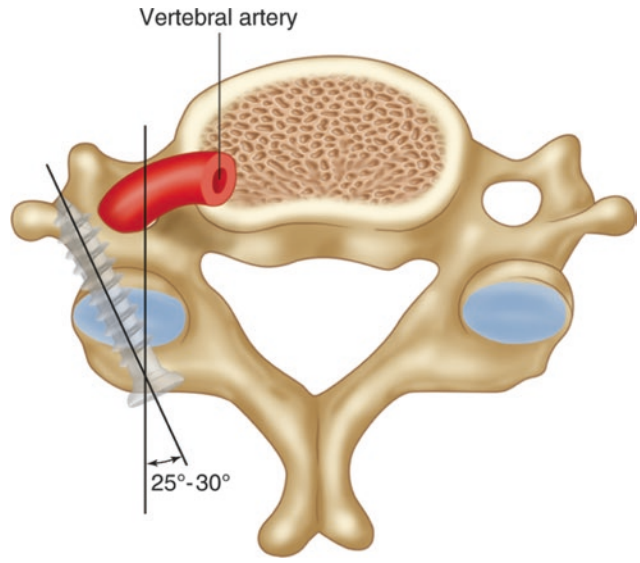

Fig. 12.6 Placement of lateral mass screws in a cervical vertebra

ments (C1 and C2). Cervical vertebrae have anatomical structures not found elsewhere in the spine called the lateral masses, which are more amenable for screw placement than cervical pedicles. Placement of lateral mass screws and rods provides equal or greater biomechanical stability when compared to anterior plating or interspinous wiring techniques [6] (Fig. 12.6). Placement of lateral mass screws does not depend on the integrity of the laminae, pedicle, or spinous processes to achieve fixation as is the case of cervical wiring and pedicle screws. The limitations of lateral mass fixation include risk of injury to the adjacent nerve roots, vertebral arteries, or facet joint [6, 7].

Similar to ACDFs, multimodality monitoring using SSEPs and Tc-MEPs to monitor the spinal cord and EMGs to monitor the nerve roots is the preferred monitoring plan for PCF.

Cervical Corpectomy

When the cervical disease involves more than just a single disc space, it may be necessary to remove part of the vertebral body and adjacent

discs in a procedure called a corpectomy. This can be necessary for multilevel stenosis, tumor removal, or vertebral infection. The approach is similar to that of an ACDF. Once a majority of the affected vertebral bodies and disc material have been removed, a graft—typically shaped bone or a stackable cage—is fitted to support the anterior vertebral column (Fig. 12.7). The cervical spine is further stabilized with a metal plate and screws similar to that used in an ACDF. If the spine appears unstable after the anterior corpectomy, a PCF may be necessary to provide long-term stability. Recommended IOM is similar to that of an ACDF [8].

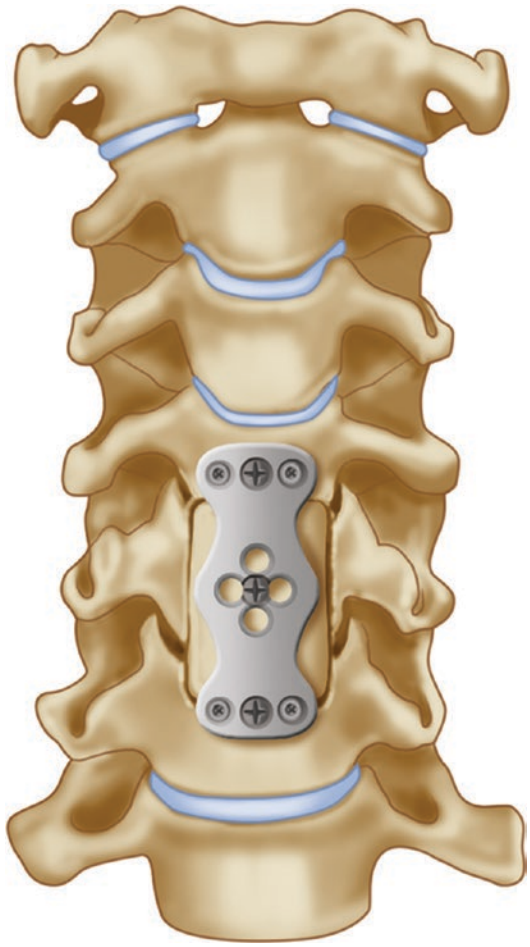

Fig. 12.7 Following removal of the vertebral body, a wedge-shaped bone graft is inserted into the space created by the corpectomy and is stabilized using a screw and plate system similar to an ACDF

Procedures of the Thoracic Spine

The thoracic vertebrae—T1 through T12—attach to the posterior rib cage. Due to the presence of the ribs and position of the spinous processes, the thoracic spine is stiff and motion is limited. This immobility can put strain on the adjacent cervical or lumbar spine, making the areas from C6 to T2 and T11 to L2 especially susceptible to injury. Commonly trauma or metastatic lesions are the cause of thoracic spine surgery. Thoracic laminectomy, corpectomy, and fusion are performed similarly to other levels. Burst fractures (discussed below) are often seen in the lower thoracic segments. Commonly monitored procedures of the thoracic spine are for correction of scoliosis and spinal deformity.

Surgery for Scoliosis Correction

Scoliosis describes an abnormal, lateral, curvature of the spine. The two most common forms of scoliosis are neuromuscular and idiopathic (also called adolescent). Neuromuscular scoliosis is usually caused by a deterioration of the facet joints and occurs most commonly in people over 65. Surgery is often performed to reduce pain. Older patients may have osteoporosis and may require many levels of instrumentation to achieve a complete fusion. Idiopathic, or adolescent scoliosis, is seen in children and teenagers and is often discovered during routine doctor's exams. It is necessary to prevent the curvature from progressing as the child ages. If the curve measures <20°, surgeons often choose to brace the spine or continue to observe the progression of the curvature. Surgery for adolescents with scoliosis is only recommended when the curvature is >45° and continuing to progress [9]. A high degree of curvature may put the patient at risk for cardiopulmonary compromise as the curve of the spine rotates the chest and decreases the vital capacity (ability to breathe).

Scoliosis correction procedures are extensive and may require both an anterior and posterior approach in severe cases. Correcting the scoliosis involves applying different forces to the spine

including distraction and rotation. These maneuvers place the spinal cord at risk for either direct injury or regional ischemic injury as blood vessels become compressed.

Posterior fusion for scoliosis correction involves a long incision and exposure through the posterior musculature to access the bony elements of the spine. Instruments such as hooks and screws are attached to the vertebrae and serve as anchors for long rods that straighten and hold the spine in the correct position (Fig. 12.8). Bone graft is then added along the spine to facilitate a permanent fusion. An "anterior release" may be necessary prior to posterior instrumentation for patients with a severe deformity. This procedure is typically done with a lateral approach where the intervertebral discs are removed from the front to allow for more spinal movement and to encourage bony growth once the spinal curvature is corrected.

For corrections that are mainly needed at the thoracolumbar junction (T12–L1), the surgery can be performed via an anterior approach. The discs are removed to loosen up the spine, screws are placed in the vertebral bodies, and rods are used to reduce the curvature. An anterior technique has minimal blood loss and muscle damage compared to a posterior or anterior–posterior procedure. Additionally, not as many lumbar segments need to be fused thereby preserving some motion segments reducing the risk for future back pain. The anterior approach can only be done on thoracolumbar curves and most idiopathic scoliotic curves involve the thoracic spine.

Multimodality spinal cord monitoring using SSEPs and MEPs has become a standard of care for scoliosis surgery. SSEPs may also help prevent postoperative neuropathy or plexopathy as these procedures can be quite lengthy [3, 10, 11]. Injury to the thoracic spinal cord can produce abrupt bilateral or unilateral leg MEP loss and/or a decrease in lower extremity SSEP amplitude [12], and the surgeon can be immediately notified. While thoracic levels T2–T7 are not amenable to EMG monitoring, lower thoracic and lumbar levels can utilize free-running EMGs to reduce risk to spinal nerve roots. The anal sphincter should also be monitored when instrumenting at thoracolumbar levels due to the presence of the conus medullaris and risk to the extending cauda equina.

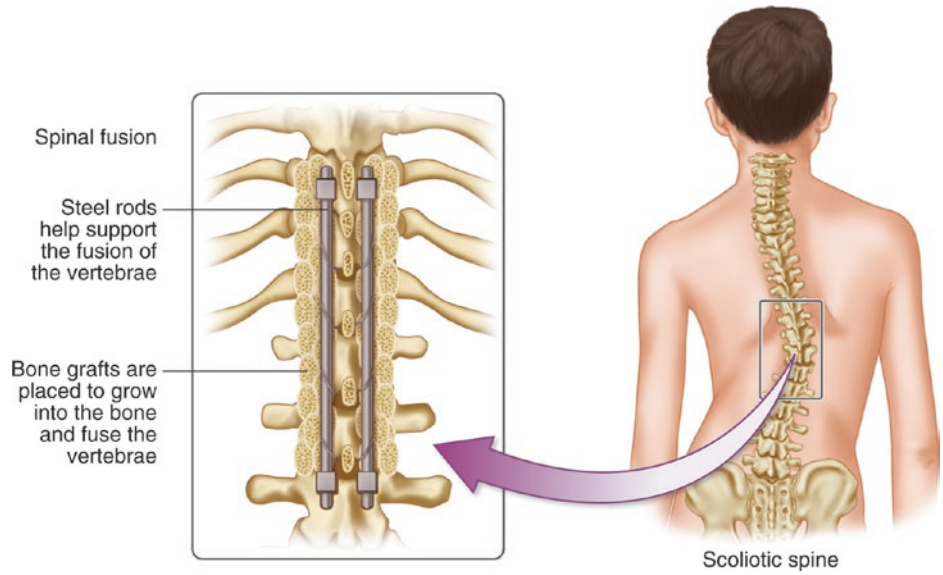

Fig. 12.8 On the *right* is an example of scoliosis. Notice the curvature creates an asymmetry that is visible in the stance of the patient. On the *left* is a corrected curve being held in place with rods. Bone graft is in place to facilitate bony fusion

Thoracolumbar Trauma

Trauma to the spine indicates that an injury has occurred to any or all of the following components: bony elements, ligamentous (soft) tissues, and neurological structures. While injury does not always indicate the need for surgical intervention, mechanical instability and potential neurological injury are two concerns for spinal traumas. Instability is usually the result of a fracture in one of the major bony components (vertebral body, pedicles, lamina) of a vertebra. An unstable fracture may not allow the spine to withstand normal load-bearing activities without further risk of a neurologic injury. Classification methods for thoracolumbar fractures are based upon the mechanism of failure and the column of the spine affected. The spine is viewed as having three columns when viewed laterally. There is an anterior, middle, and posterior column [13] with the middle column the most important for stability (Fig. 12.9). Trauma to the spinal column can result in compression (burst) fractures, anterior and posterior element injuries with distraction, and anterior and posterior injuries with rotation [14]. Burst fractures can be highly unstable and generally occur when a violent compressive load results in failure of both the anterior and middle spinal columns. This severe compression of the vertebral body may be associated with extrusion of bony fragments into the vertebral canal putting at risk the spinal cord and cauda equina (Fig. 12.10). Burst fractures can be treated by a procedure known as kyphoplasty. Guided by fluoroscopy, a needle is inserted into the vertebral body then a balloon is inflated to restore height, thereby creating a space where bone cement can be injected to stabilize the fracture. Multimodality monitoring for trauma surgery of the spine can help reduce further injury to the neural elements as well as possibly providing information on the functional neurological status of the trauma patient that has just arrived to surgery from the ER.

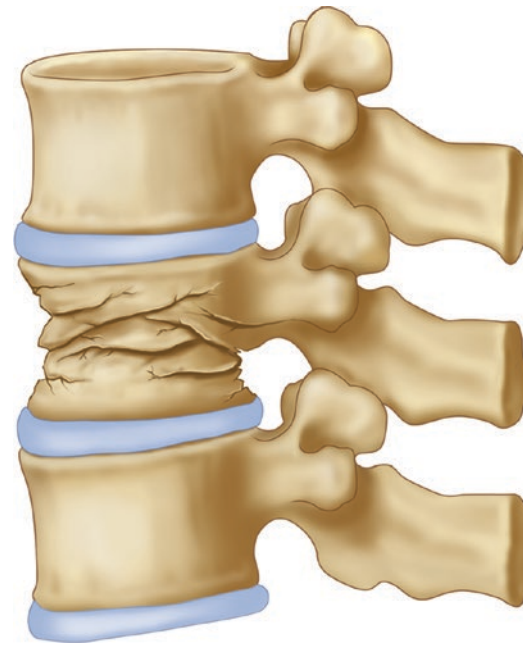

Fig. 12.10 An example of a burst fracture viewed laterally

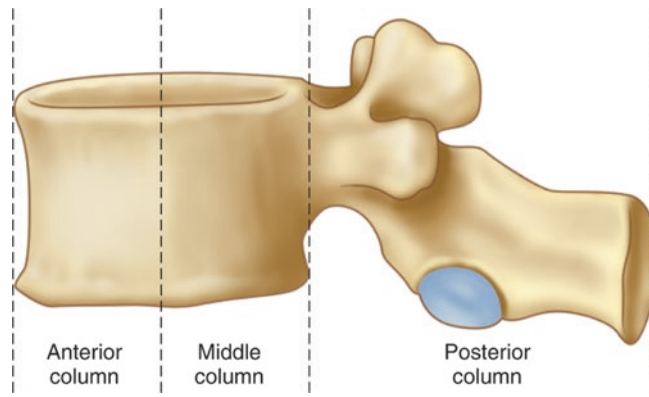

Fig. 12.9 The spine is viewed as having three columns when viewed laterally. The *middle column* is the most important for stability and load bearing

Procedures of the Lumbosacral Spine

The lumbar spine—L1 through L5—supports the weight of the body. The vertebral bodies are much larger in order to absorb the stress of lifting and carrying. Below the lumbar region, the sacrum connects the spine to the hipbones. Below the sacrum, the coccyx completes the spine and provides attachment for ligaments and muscles of the pelvic floor. Common spine-related conditions that can cause lower back and lower extremity discomfort include disc herniation, degenerative disc disease, spondylolisthesis, spinal stenosis, and sacroiliac joint dysfunction. Minimally invasive (MIS) procedures such as a microdiscectomy or laminectomy may be able to relieve pain caused by central or foraminal stenosis. In the most serious cases, when the condition does not respond to conservative therapies such as physical therapy or pain management, a spinal fusion may be necessary to strengthen the spine and prevent motion in the vertebral segment(s) causing pain.

Below vertebral level L1, the vertebral canal contains the cauda equina. The cauda equina contains the lower lumbar and sacral spinal nerves traveling toward the appropriate level where they exit and innervate the lower extremity. Nerve roots can be injured during lumbosacral surgery by retraction, compression, electrocautery, drilling, or misplaced hardware. One of the most common postoperative deficits is foot drop caused by injury to the L5 nerve root. Other postoperative deficits can include numbness, weakness, and bowel or bladder dysfunction. SSEPs are not sensitive to detecting nerve root injuries; therefore free-running and triggered EMG along with Tc-MEP are the primary modalities most often used to monitor nerve root function. Depending on patient anatomy and the lumbar levels requiring fusion, there are different approaches to the spine that are utilized during surgery including posterior, anterior, and lateral approaches.

Posterior Lumbar Interbody Fusion

During a posterior lumbar interbody fusion (PLIF), the spine is accessed through an incision in the midline of the back and the large erector spinae muscles are retracted. Once the proper spinal levels are exposed, a laminectomy and often a discectomy are performed with the goal of decompressing the neural elements. If a discectomy is to be performed, it is followed by placement of a cage in the disc space (typically made of bone or synthetic material) that restores height to the disc space and assists in bone growth. Bone graft is added to provide a matrix for additional bone growth. The level is stabilized using pedicle screws and rods while fusion takes place (Fig. 12.11).

The monitoring plan for a PLIF consists of upper and lower SSEPs to monitor the spinal cord and for positional injury [3, 10, 11]. Although the surgery is not at the level where the spinal cord is present, the addition of SSEPs can still be useful in detecting ischemia as a result of hemodynamic changes.

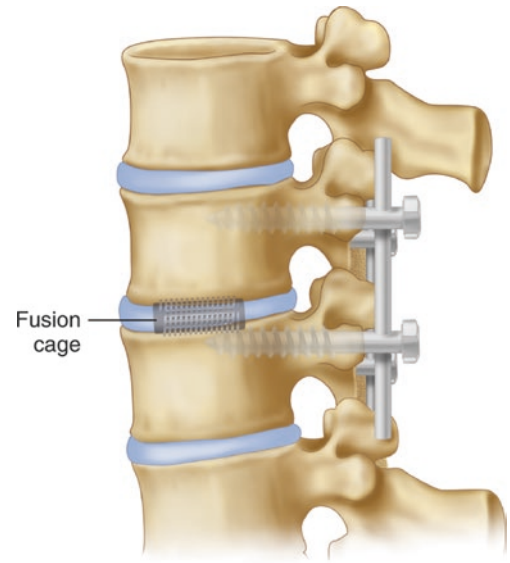

Fig. 12.11 The result of posterior lumbar interbody fusion. Following a laminectomy and discectomy, a bone graft was placed in the disc space. Screws and rods were inserted to stabilize the spine until the bony fusion is complete

Spontaneous EMG for nerve root monitoring is typically recorded continuously during surgery, so it is very important for anesthesia to not administer any neuromuscular blockade after intubation. Activity is recorded from myotomes corresponding to the nerve roots at risk, and irritation resulting in "train firing" or "neurotonic discharge" should be immediately reported to the surgeon. In addition to free-running EMG, stimulus-triggered EMG has become a standard technique used during pedicle screw insertion. Triggered EMG relies on the concept that intact cortical bone should electrically insulate a properly placed pedicle screw from the adjacent nerve root. By stimulating the pedicle screw directly using a monopolar probe, a properly placed screw should not elicit any muscle response below a stimulus of 10 mA. With a medial pedicle breach, either directly by the screw or from a crack in the pedicle wall, electrical stimulation will activate adjacent nerve roots, evoking compound muscle action potential (CMAP) responses in muscles from the appropriate myotomes at a stimulus <7 mA [15–17]. Some types of pedicle screws, such as those coated with hydroxyapatite, have an extremely high electrical resistance and cannot accurately or safely be stimulated [18]. In these cases, stimulating the pilot hole or tap (instrument) prior to placement of these screws is recommended. Patients with advanced osteoporosis may have lower than expected impedances and may trigger false-positive responses. Alternatively, patients with chronically compressed nerve roots may require a much higher stimulus intensity to evoke a CMAP response. The surgeon may also wish to stimulate a nerve root directly using t-EMG for identification or to test function.

Anterior Lumbar Interbody Fusion

An alternative to the PLIF is an anterior lumbar interbody fusion (ALIF). For this procedure, the spine is accessed through an abdominal incision more commonly on the left side. This retroperitoneal approach allows access to the spine without disturbing abdominal structures. The anterior approach gives better access to the disc space so more disc material can be removed and a larger spinal implant can be used. With an ALIF, there is minimal damage to the large stabilizing spinal muscles and the spinal nerves remain largely undisturbed. The procedure is performed in close proximity to the major blood vessels (aorta, iliac artery, vena cava, and iliac vein) that supply the legs [19, 20]. Vascular surgeons often assist in retracting the blood vessels during exposure for these procedures (Fig. 12.12). Lower extremity SSEPs are performed while retractors are in place to monitor for vascular compromise.

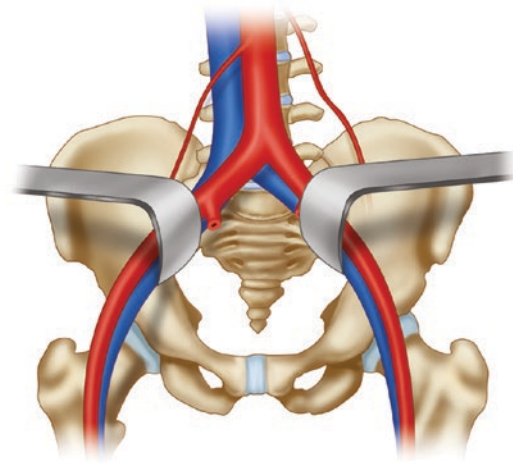

Fig. 12.12 Retraction of major blood vessels is required for access to the vertebral bodies and disc space during an ALIF

Minimally Invasive and Lateral Approaches to the Lumbar Spine

MIS approaches to spine surgery are designed to offer decompression and fusion through a smaller incision resulting in reduced tissue damage, blood loss, less postoperative discomfort, and a quicker recovery time. Procedures such as a microdiscectomy or laminectomy can be done

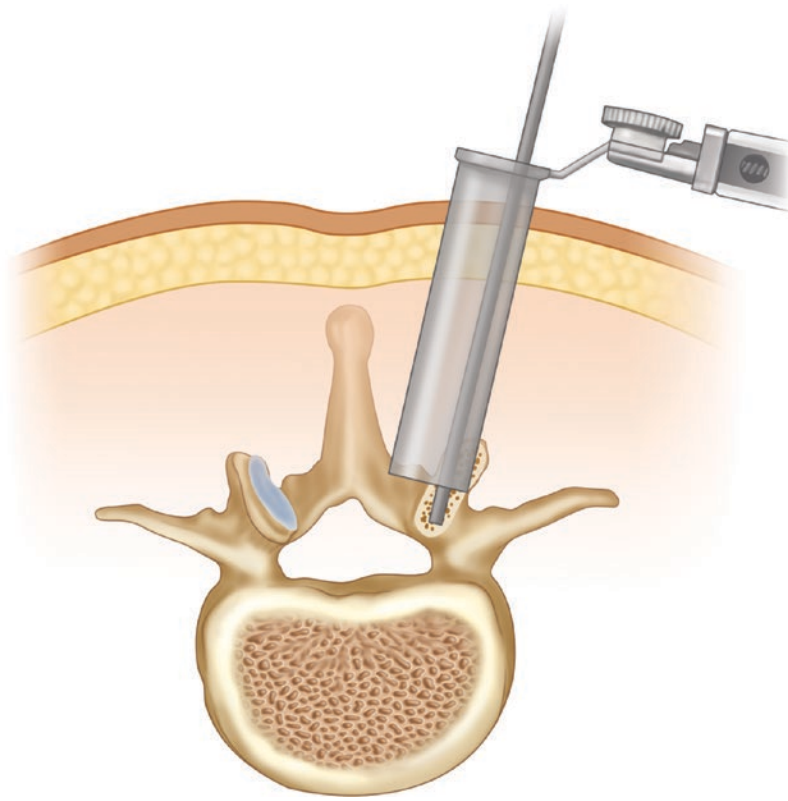

Fig. 12.13 Minimally invasive approaches to spinal surgery involve the use of tubular dilators for access

through a very small incision and the insertion of tubular dilators to enlarge the space (Fig. 12.13). IOM can be valuable to the surgeon during these procedures because the incision is small and the spine is not largely exposed, making anatomical landmarks challenging to identify [21].

A lateral approach to perform a spinal fusion is considered a minimally invasive surgery (or MIS) procedure [22]. Instead of a long posterior or anterior incision, the surgeon makes one or more smaller incisions on the patient's side and uses a dilator/retractor system to expose and visualize the spine. A lateral approach does not require major organs or blood vessels to be moved. Once the spine is exposed, a standard discectomy is performed and a large cage is implanted in the disc space. A lateral plate or posterior instrumentation may be used to further secure the implant and stabilize the spine.

To access the disc space, the surgeon must navigate through the large psoas muscle and in close proximity to nerves of the lumbosacral plexus (Fig. 12.14). Free-running and triggered EMGs are critical during lateral approaches as these modalities can help identify the location of nerves in the lumbar plexus during exposure and retractor placement. Upon placement of the retractor, the surgeon may wish to further verify the absence of neural tissue with an electrically stimulated monopolar probe. A more recent approach, the oblique lateral interbody fusion (OLIF), is another lateral approach that gives surgeon lateral access but allows them to avoid the psoas and the iliac crest [23].

While not as routinely used as EMGs during lateral procedures, lower extremity SSEPs can be utilized to monitor the nerves of the lumbar plexus, and both upper and lower extremity SSEPs can be used to monitor positional effects.

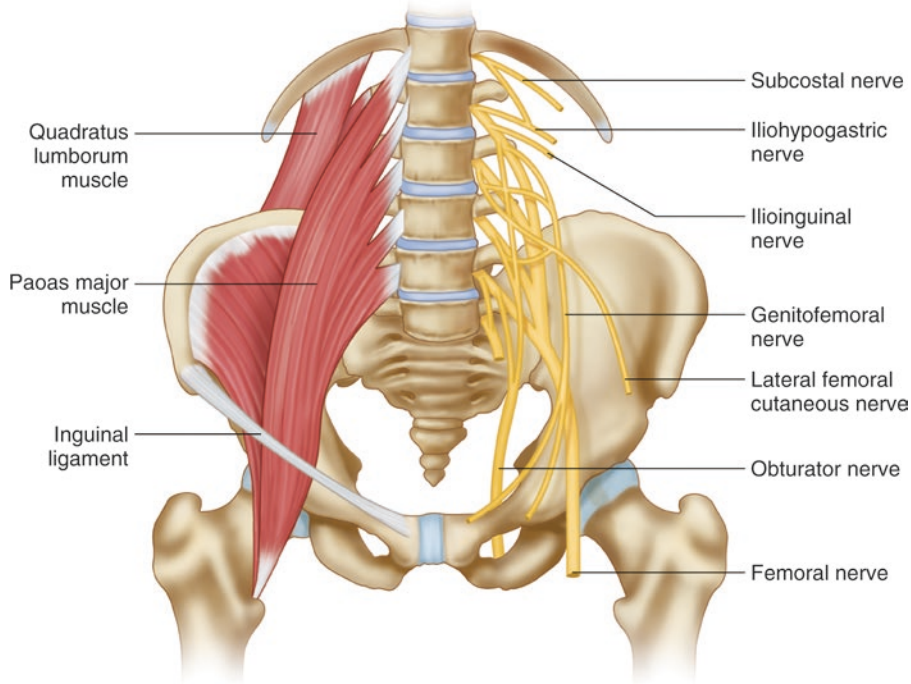

Fig. 12.14 The transpsoas approach to lateral access spine surgery puts elements of the lumbar plexus at risk

Conclusion

Spine surgery places at risk the spinal cord, nerve roots, nerve plexuses, and peripheral nerves. A multimodality approach to intraoperative monitoring utilizing SSEPs, Tc-MEPs, and EMGs can provide real-time feedback to the surgical team and reduce the risk of permanent neurologic injury.

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13 Monitoring and Mapping of the Spinal Cord

Christopher J. Pace

Surgery for IMSCT

Intramedullary spinal cord tumors (IMSCTs) are rare, often benign, lesions of the spinal cord and surgery continues to be the major option for treatment. The goals of surgery include satisfactory oncological resection to rid the patient of cancer while preserving the delicate neural structural and functional integrity of the spinal cord. Several factors play into the development of the surgical strategy and the choice of selective versus gross total resection. Of these, the tumor type, tumor grade, spinal location, number of spinal levels, and the patient's preoperative neurologic status are among the most important [1–5]. As such, ependymoma and hemangioblastoma lesions, which comprise 45% and 5%, respectively, of the IMSCTs lend themselves to gross total resection especially if there is a clear plane of resection. Ependymomas occur more often in adults, are found centrally in a cross-section of the spinal cord, are more common in the lower spinal cord, are often encapsulated, are associated with cysts, and appear uniformly dense on imaging. Hemangioblastomas are the least prevalent of the most common IMSCTs. They arise from blood vessels and their resection may have a greater likelihood of neurophysiologic changes than ependymomas [6]. Astrocytomas, which comprise 40% of IMSCTs, are often treated with partial surgical resection because these tumors tend to be infiltrative with associated poorer prognosis. Astrocytomas are more common in children, tend to be eccentric in a cross-section of the spinal cord, can be found at all levels of the spinal cord, and most commonly occur at the thoracic levels. The remaining IMSCT types are rare. The strategy for any IMSCT tumor type may revert to sub-total resection if the intraoperative neurophysiologic monitoring (IONM) data indicate significant risk to spinal cord function.

For IMSCT surgery, a common approach is posteriorly. For this reason, patients will be operated in the prone position. On the occasion where the tumor is lateralized, the surgeon may choose to approach the spine from the side and the patient may be positioned in the lateral oblique position. For patients in the prone position, arms will be in one of two positions. For lesions at lower spinal levels, the "superman" position will be used, the upper arms perpendicular to the plane of the body from shoulder to elbow, and then 90 degrees again from that plane, back to parallel with the body from elbow to hand, with fingers resting palm-down on either side of the patient's head. For lesions at or above the mid-thoracic level, the arms will be tucked along the plane of the body with the fingers pointing toward the feet and the thumbs down for ergonomic continuity. Extra care should be exercised when

C. J. Pace (✉)
Neuro Alert and Center for Electroneurodiagnostics, White Plains, NY, USA
e-mail: cpace@neuroalert.com

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securing the electrodes to the arms, wrists, and hands as once the patient is positioned and the arms are tucked, the wrap will limit access to the placed electrodes should the need arise to replace or reposition them.

The spinal canal is exposed by laminectomy, and occasionally the strategy is to reconstitute the spine by laminoplasty. The laminectomy extends just superior and inferior to the expected extent of the solid portion of the lesion and may be extended if necessary. Through the window that is now opened into the spinal canal, the surgeon may choose to employ ultrasound to confirm tumor location.

This is followed by durotomy. Commonly, the dura is pried from the underlying spinal cord using micro forceps. A small hole is made through which the tip of a nerve hook is inserted, lifting the dura away from the spinal cord. Working along the long axis of the spinal cord, a scalpel incision is made and extended using the nerve hook as both a tool for lifting the dura and one against which force can be safely applied with the scalpel, thus protecting the spinal cord beneath it. The dura is opened long-wise and when opened resembles an open eye (where the open dural flaps on either side of the cord are the eyelids, and the spinal cord proper the globe of the eyeball). Traction is applied with dural sutures that are either anchored to the surrounding tissue or to a hemostat clamped to the distal end of the suture and dangled over the side of the patient. Once the dura is opened, the arachnoid is incised.

When D-wave recording is part of the monitoring strategy, after the dura is open and retracted, the surgeon will slide a spinal recording electrode epi- or subdurally under the lamina of spinal segments caudal to the surgical site (Fig. 13.1). Whenever practical, a second spinal recording electrode is worked rostrally in the same fashion. The insertion point of the spinal electrode may be gently irrigated to facilitate placement and to promote good contact. Epidural spinal electrodes can also be placed transdermally using a Touhy needle, but this is rarely necessary in open IMSCT surgery.

D-waves are notoriously sensitive to electrode position, and spinal electrodes are prone to being displaced and dislodged. Maintaining the electrode in its original position throughout the salient surgical steps is critical for the reliability and interpretation of D-waves. Once the spinal electrode has been placed, its position may be fixed in place in several ways:

- Stabilize the wire exiting the spinal electrode using the surgical drape clamped around the wire with a hemostat. Be sure to check that the delicate wire of the spinal electrode has not been clamped directly as this may cause interruption of the wire and/or its insulation, resulting in poor recordings.
- Encourage the surgeon to suture around the epidural electrode as it exits the dura and affix it to the surrounding tissue.
- Take note of the position and location of the electrode even if with a photograph. This can be aided by putting a fiducial mark on the epidural electrode as it exits the epidural space. Spinal electrodes often have fiducial marks of their own.

We encourage the neurophysiologist to attempt D-waves promptly after the placement and plug-in of the spinal electrodes. This gives time to troubleshoot the contact and placement of the spinal electrode(s) and optimize the stimulation parameters.

Once an optimized D-wave has been obtained and reported, spinal cord mapping may follow. The mechanics of the mapping depend on the method of choice (see below), but they include handoff of a sterile electrode required to stimulate directly or record directly from the spinal cord. Often, access into the spinal cord is at the posterior median sulcus which separates the left and right gracile fasciculi. Anatomically, the posterior median sulcus is at the midpoint between the dorsal root entry zones located at the lateral edges of a normal spinal cord. The visually estimated anatomical midline is compared with what is determined neurophysiologically to better approximate the location of this sulcus.

The spinal cord is opened by posterior midline myelotomy down the posterior median sulcus. This may be initiated directly by scalpel or by

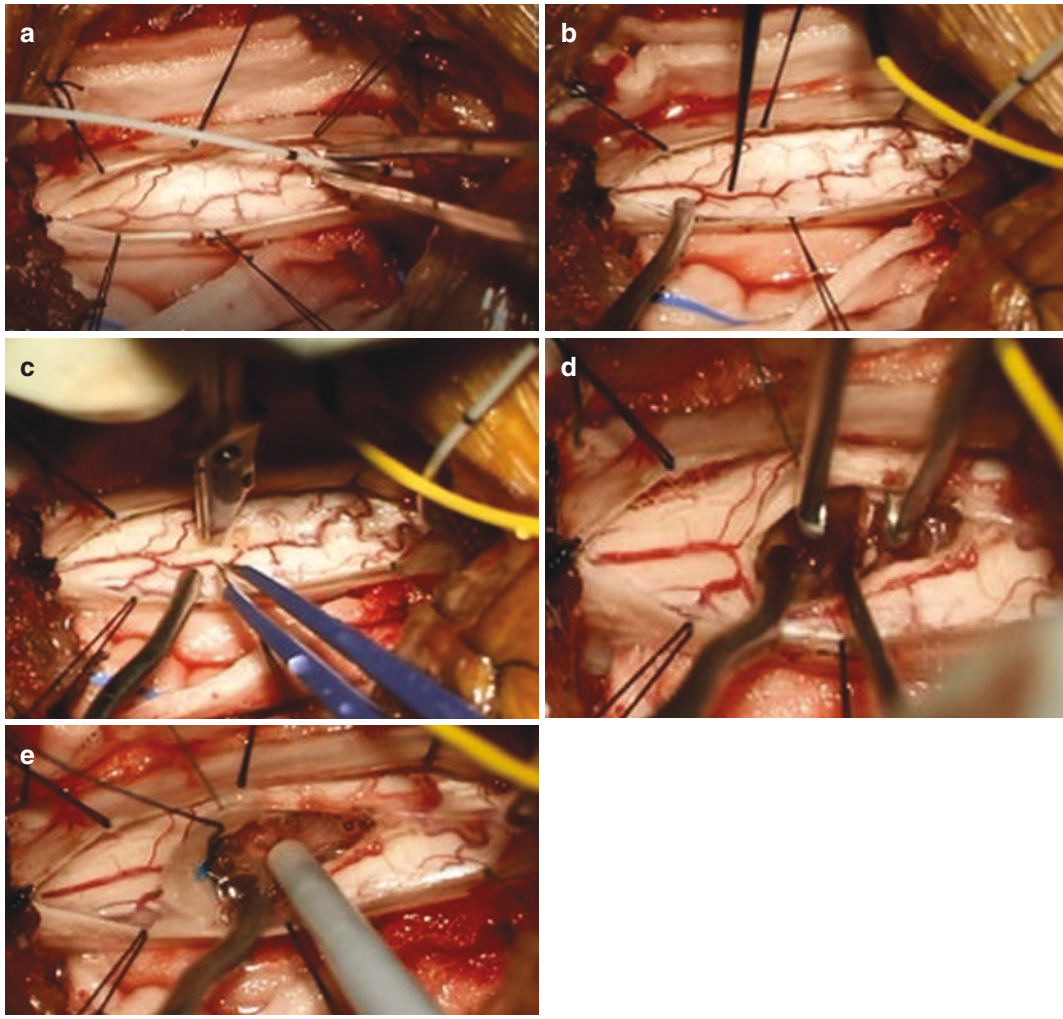

Fig. 13.1 Intraoperative images through the microscope of various stages of surgery for a mid-cervical IMSCT. (**a**) Placement of the spinal electrode used for recording D-waves. In this figure, the dura is open and retracted using stitches, seen here in black, revealing the vascularized spinal cord in the center of the image. The spinal electrode, seen here with two of three contacts visible, is gently guided by the surgeon into the epidural space inferior to the location of the lesion. (**b**) Stimulation of the spinal cord with a monopolar probe during dorsal column mapping. (**c**) Midline dorsal myelotomy via scalpel. (**d**) Tumor retraction and tumor forceps. (**e**) Cavitron ultrasonic aspirator (CUSA)

coagulation of dorsal midline veins and the superficial and medial aspect of the penetrating/diving fissure. The myelotomy is extended either with a scalpel or by splaying the cord via the outward pressure from the opening of closed micro forceps or the tips of the bipolar electrocautery device, with or without accompanying incising. Once the myelotomy is complete, some surgeons prefer to retract the dorsal columns either manually or with small sutures (such as pial traction sutures). Somatosensory evoked potentials (SSEPs, see below) are the focus of the IONM during these stages of the surgery. SSEP signal changes secondary to retraction forces applied on the dorsal columns indicate adjustments to retraction and/or the myelotomy are warranted. The surgeon should be encouraged to relax the tension on the tissue by either directly reducing retraction or indirectly by extending the myelotomy which allows the dorsal columns to open more freely.

Following the opening of the spinal cord, other types of mapping may ensue including localizing and even mapping the contents of the descending motor tracts through direct spinal cord stimulation. Selective or continuous mapping such as this may be incorporated throughout the resection.

Work on the tumor begins. A tissue specimen for biopsy is obtained using tumor forceps since the pathological identification of the tumor type is integral to the development of the surgical strategy and resection objectives. If there is a cystic component of the lesion, this may aid in identifying the leading and trailing ends of the tumor and help establish the resection plane. A cystic component of the tumor may make it difficult to obtain D-waves. While portions of a tumor that are clear and distinct from normal tissue may be removed by direct excision, tumors are typically debulked in an inside-out fashion. This is accomplished with the use of tumor forceps, electrocautery, or with a Cavitron Ultrasonic Surgical Aspirator (CUSA). The CUSA uses high-frequency sound waves to morselize the tumor tissue, while preserving healthy tissue. These mobilized tumor fragments are suspended by irrigation fluids and aspirated away through the CUSA.

Working the marginal edges of the tumor and the tumor capsule from the surrounding nervous tissue is a critical stage of the surgery. Transcranial motor evoked potential (TcMEP) and D-wave monitoring is the focus of the IONM at this stage of the surgery. Tumor traction is often applied using the force generated by long-wise sweeps of the suction. Gentle counter traction on the spinal cord accompanied by isolation, division and electrocautery of adhesions and blood vessels are keys to successful excision.

At the completion of the tumor work, the dura is sutured closed. The surgeon will often request a Valsalva maneuver after the dura is closed to verify the integrity of the closure by looking for cerebrospinal fluid leaks during the period of higher intraspinal pressure temporarily created by the Valsalva. The epidural electrode(s) is/are likely to be removed at this point. Monitoring of D-waves should continue until the electrode(s) is/are removed. SSEP and TcMEP monitoring should continue until skin closure [7].

IONM in IMSCT Surgery

There are a number of published studies that represent the important contribution that spinal cord IONM and spinal cord mapping make to the surgical treatment of IMSCTs [7–20]. The monitoring modalities of SSEP and TcMEP, the most common IONM approaches during IMSCT surgery, and electromyography (EMG), a less commonly incorporated modality in IMSCT surgery, have been addressed in detail in other sections of this text. Therefore, the focus here will be on the addition of D-wave recording and on the methods of spinal cord mapping focusing on the dorsal columns and the corticospinal tracts (CSTs).

For IMSCT surgery, IONM including SSEP and TcMEP for monitoring spinal cord function should commence early. Patients with IMSCTs can be challenging neurophysiologically since they often have clinical or subclinical neurologic compromise. Pre-positioning baselines should be part of the IONM strategy for each of these cases. Post-position baselines without pre-position references introduce questions about the reason behind any incomplete or absent IONM data after positioning. Pre-position baselines also permit the surgical neurophysiologist the opportunity to evaluate and discuss the recordings and implement plausible adjustments to the IONM strategy to try to overcome deficiencies in data should they exist. Integrally, the surgical neurophysiologist must provide a thorough and detailed description of the pre- and post-positioning IONM recordings, as they should do throughout the procedure.

Somatosensory Evoked Potentials

For an in-depth view of SSEPs, I recommend the reader review Chap. 6 and the Association guidelines [21–23]. An SSEP is the bioelectric activity that originates from the nerves, tracts,

and synapses along the ascending dorsal column-medial lemniscal (DCML) pathway. This pathway starts with the axons of dorsal root ganglia neurons that have terminal ends in the periphery. These axons, that carry fine touch, vibration, and proprioceptive information from sensory organs in the skin and from muscle spindles, course up the limb and into the lumbar plexus and lumbosacral plexus for axons of the lower limbs and the brachial plexus for axons of the upper limbs. They traverse the lateral neural foramen and pass into the spinal canal, transitioning from the peripheral to the central nervous systems. Each axon courses superiorly before approaching the spinal cord via the dorsal rootlets. Caudocranially, there is decreasing distance between the spinal level at which each axon enters the spinal column and the level at which it penetrates the spinal cord. Axons of the lower extremity course up the cauda equina, a distribution of nerve roots in the spinal canal ensheathed in the thecal sac, and enter the spinal cord at or just above the conus medullaris around spinal level L1.

After penetrating the spinal cord, the axons enter the posterior tracts, also known as the dorsal columns, and ascend the spinal cord toward the brainstem in distinct, somatotopically arranged, parallel tracts. The axons of the lower extremity course in the gracile fasciculi which bookend the posterior median sulcus. As you move up the spinal cord, axons from the trunk and then from the upper extremity systematically and successively join the dorsal columns laterally. In the cervical spine, the more lateral tracts, which are composed predominantly of the axons of the upper extremity, are the cuneate fasciculi.

In the direct, ascending pathway these axons make their first synapse in the gracile and cuneate dorsal column nuclei of the medulla. Axon collaterals also synapse in the spinal cord, participating in intraspinal neural circuits such as reflex arcs. The gracile and cuneate nuclei are independent regions of the medulla and maintain the separation of these parallel afferent pathways. Axonal projections from neurons in the gracile and cuneate nuclei decussate the brainstem in the internal arcuate of the medulla before ascending in the medial lemniscus toward the thalamus. Of note, a small percentage of patients have a non-decussating sensory pathway.

The ventral posterior nucleus of the thalamus is where the second synapse in the direct DCML pathway is found. The thalamus serves as a processing and relay center, and the pathway continues to the cortex from there. Thalamocortical projections make their way through the posterior limb of the internal capsule until they synapse on cortical pyramidal cells located primarily in the postcentral gyrus of the parietal lobe (the primary sensory cortex). Thalamocortical axons project to homonymous and somatotopically arranged cortical neurons: those axons corresponding to the lower extremity project medially along the interhemispheric medial bank and those axons corresponding to the upper extremity project laterally. The pathway continues through intracortical circuits of higher sensory processing.

SSEPs for spinal cord monitoring are initiated via transdermal electrical activation of peripheral nerves, typically as they come near the surface of the skin in the wrists and ankles. The ulnar nerve in the wrists and the tibial nerve in the ankles are a good choice for IMSCT surgery. In the case of a tumor situated high in a patient's cervical spinal cord and informed by the patient's neurologic presentation, adding median nerve SSEPs is recommended as they help to triangulate the location of an SSEP data change should one occur. Be prepared to activate the nerves of the popliteal fossa as well, since lower extremity SSEPs originating from the ankle may be difficult to resolve depending on the amount of neurologic functional compromise imposed by the tumor. Keep in mind this will result in greater patient movement, which can negatively impact the frequency at which they can be run. Popliteal fossa electrodes are also advantageous for recordings of antidromically transmitted action potential volleys elicited through stimulation of the spinal cord during dorsal column mapping (see below) and therefore can serve multiple purposes.

Nerves are activated with surface or, preferentially, with subdermal needle electrodes. At the ankle, the anode is placed behind the medial malleolus for tibial nerve activation. At the wrist, the

anode is placed just proximal to the crease of the wrist and lateral to the flexor carpi ulnaris tendon for ulnar nerve activation and between the flexor carpi radialis and palmaris longus tendons for median nerve activation. The cathode is placed 2–3 cm proximal to the anode. For popliteal fossa activation, the anode is placed midway between the tendons of semitendinosus and biceps femoris above the crease behind the knee and the cathode is placed 2–5 cm proximal to the anode and 0–2 cm lateral to midline. Constant current, 200–500 μsec, square pulse, repeating stimuli are applied asymmetrically and alternately. Stimulation frequency, or repetition rate, is typically between 2 and 6 Hz, selecting values that de-harmonize with noise at the electrical line frequency. Higher repetition rates allow for faster acquisition of trials but simultaneously can result in degraded signal. Notwithstanding the longer acquisition time, it may be helpful to reduce the repetition rate, as lower stimulation frequencies may improve the resolution of poor signals. Signal acquisition sweep is typically 100 msec for lower extremity SSEPs and 50 msec for upper extremity SSEPs; however, increasing these time bases should be considered if the lesion has induced a latency delay. The intent of the acquisition sweep is to choose one that collects the major deflections of the response near the middle. Longer acquisition sweeps will consequently limit the high end of employable stimulation frequency as successive recording trials cannot overlap. Stimulus intensity, starting at 20 mA and 30 mA for upper and lower extremity, respectively, is ramped up, if necessary, until a supramaximal response is detected. Employing higher stimulus duration or intensity increases recruitment but consequently increases the likelihood of current spread inadvertently activating a nearby nerve(s), particularly when stimulating at the wrist. Therefore, a possible decrease in specificity must be considered when using higher stimulus intensities and durations.

SSEPs are small potentials and are often obscured by noise. To help resolve these potentials, we employ averaging. Starting at 200–500 trials is recommended, but the effective number of trials depends on the signal-to-noise ratio. At critical times in IMSCT surgery quick feedback is important, so fewer trials per average is advantageous.

Recordings of SSEPs are obtained at select locations on the body so as to maximize the likelihood of sampling the activity in a given portion of the pathway. Integrating information on the nature of the SSEP responses at each location and relative to those recorded earlier in the procedure helps to localize the source of signal change and/or decipher or discount systemic causes.

Peripheral recording sites include the popliteal fossa for lower extremity SSEPs and the supraclavicular fossa for upper extremity SSEPs. These sites capture predominantly high-frequency traveling waves coursing through the underlying nerves, and are intended, in large part, as a checkpoint to confirm activation of the pathway. Popliteal fossa recordings are captured with the reference electrode placed medially in the leg just above the crease behind the knee. In a bipolar montage the active electrode is 2–5 cm proximal and 0–2 cm lateral. In a referential montage the reference electrode is at a distant site. Erb's point potentials are often captured at supraclavicular fossa recording sites using a referential montage where the left and right electrodes are referred to each other. A starting low-frequency filter (LFF) and high-frequency filter (HFF) of 30 and 1500 Hz, respectively, and an amplifier sensitivity of 20 μV/Div, works well to capture these high-frequency, often large, potentials. The obligate peak of the response obtained at these sites occurs at approximately 7–9 msec and is identified as N9. The latency of N9 and its amplitude relative to the trailing positive trough are tracked.

Recording sites near the neck and in the scalp are included to capture synaptic activity in subcortical structures such as the brainstem and thalamus and the traveling waves of the tracts therein and between. These are often referred to as subcortical potentials and are captured using a "subcort" or cervical electrode placed at any of several possible locations including the inion, at the neck over the C3, C5, or C7 spinous process, at the mastoid or at the chin with a reference electrode in the scalp usually at FPz. The same recording channel is typically used for both upper and

lower extremity subcortical SSEPs. Using this montage, the subcortical potentials for lower extremity SSEPs are captured predominantly at the FPz electrode and the convention of negative potentials being upwardly deflected does not apply. Lower neck placement of the subcortical electrode is favored for resolving subcortical potentials particularly for lower extremity SSEPs. Lower neck placement may consequently capture responses from parenchymal generators, such as those that participate in spinal reflex arcs, for upper extremity SSEPs. Therefore, the surgical neurophysiologist must keep this in mind when performing IONM for high cervical IMSCTs and when focusing on the subcortical response as an indicator of spinal cord functional continuity. Placing a subcortical recording electrode in the neck may be prohibited by the surgical site and/or prepped area in which case an alternate recording site, such as the chin, inion or the mastoid, is employed. Other scalp-to-scalp and scalp-to-non-cephalic reference recording montages may be incorporated to elucidate subcortical potentials. A starting LFF of 30 Hz and HFF of 750 Hz and an amplifier sensitivity of 10 μV/Div are suitable for these subcortical recordings. For the lower extremity SSEPs, the obligate peak for the subcortical potentials is the P31, presumed to correspond to activity at the level of the dorsal column nucleus/caudal medial lemniscus. The latency of P31 and its amplitude relative to the trailing N34 are tracked. For the upper extremity SSEPs, the obligate peak for the subcortical potential is N13/P14, also presumed to correspond to activity at the level of the dorsal column nucleus/caudal medial lemniscus. The latency of N13/P14 and its amplitude relative to the trailing P18 are tracked. The N34 and the P18 are likely to originate in or around the thalamus.

Finally, potentials obtained at scalp recording sites consistent with the international 10–20 system of electrode placement and specific for localization of the postcentral gyrus, help to validate that the SSEP has arrived at the cortex. These are often referred to as cortical potentials although some generators that contribute to these recordings may be subcortical in origin. Cortical potentials are captured at scalp recording sites that are specific to the activated limb. Scalp channels for lower extremity SSEPs include CPz–FPz and CP_i–CP_c (to account for paradoxical lateralization) while those for upper extremity SSEPs include CP_c–FPz and CP_c–CP_i where the subscripts "i" and "c" denote ipsilateral and contralateral to the stimulated limb, respectively. Depending on the preferences of your practice, additional scalp electrode montages may be included for capturing cortical potentials. A starting LFF of 30 Hz and HFF of 750 Hz and an amplifier sensitivity of 10 μV/Div are suitable for these cortical recordings. For the lower extremity SSEPs, the obligate peak for the cortical potential is P37, presumed to correspond to activity at the level of mesial thalamocortical projections and synapses. The latency of P37 and its amplitude relative to the trailing N45 are tracked. For the upper extremity SSEPs, the obligate peak for the cortical potential is N20, presumed to correspond to activity at the level of lateral thalamocortical projections and synapses. The latency of N20 and its amplitude relative to the trailing P22 or P30 are tracked.

Display parameters are set and adjusted to optimize visibility. The display sweep for SSEPs will depend on the limb that is being stimulated, and on the acquisition sweep required to obtain the signal effectively. Starting sweeps are normally 100 msec for lower extremity SSEPs and 50 msec for upper extremity SSEPs increasing either or both if there appears to be a latency delay. SSEPs are normally small signals, in the range of single digit μV or even fractions of a μV so starting display gains are on the order of 1 μV/Div for lower extremity SSEPs and 3 μV/Div for upper extremity SSEPs and are adjusted according to the qualities of the signal.

Motor Evoked Potentials

For an in-depth view of muscle evoked potentials (MEPs) I recommend the reader review Chap. 7 and the Association guidelines [24, 25]. A MEP is the bioelectric activity that originates from the primary motor pathway, either from the tracts along its descending course or from its target structures, the muscles.

An overview of the primary motor pathway starts with the upper motor neurons which lie predominantly in the pre-central gyrus of the frontal lobe – the primary motor cortex. Axons that contribute to the CST, the portion of the motor pathway that projects down the spinal cord and directly modulates spinal cord motor-neuronal excitability, originate from large, motor-cortical layer V Betz cells. Upper motor neuron axons descend the cortical radiations, course through the posterior limb of the internal capsule down to the lower brainstem. At this level, approximately 85% of the fibers decussate in the pyramids of the medulla and then turn inferiorly to descend predominantly in the lateral CST. Those that do not decussate in the medulla descend predominantly in the ventral CST. The lateral and ventral CSTs modulate activity in limb and axial muscles, respectively. Of note, a small portion of patients naturally have an uncrossed motor pathway. Axons of the CSTs synapse with large, lower motor neurons – the alpha motor neurons – in the anterior horn of the spinal cord motor nuclei. An alpha motor neuron projects its axon out the ventral root of the spinal cord until it terminates at the motor end plates on muscle fibers. This neuron, the axon and all its innervated muscle fibers form the motor unit. Activity in the alpha motor neuron results in excitatory synaptic events at the neuromuscular junction; depolarization of, and initiation of the contractile mechanism in, the corresponding muscle fibers of the motor unit. It is the pre-contraction depolarization of the muscle fibers that we are detecting in our muscle MEP recordings. The activity of the alpha motor neuron, therefore, directly modulates the duration and strength of the force of contraction.

The spinal cord level of a motor nucleus roughly corresponds to the muscle location. For example, high cervical motor nuclei represent proximal upper extremity muscles and lower cervical motor nuclei represent the arm and hand, and correspondingly, upper lumbar motor nuclei represent muscles of the proximal leg whereas lower lumbosacral motor nuclei represent the distal leg and foot and non-limb muscles such as that of the anal sphincter. The spinal level and distribution of motor nuclei in the spinal cord is important to consider when formulating the IONM strategy and the selection of muscle recording sites for muscle MEP in IMSCT surgery.

When the proximal motor pathway is electrically activated either by transcranial stimulation or by direct cortical, subcortical or spinal cord stimulation a coordinated volley of descending action potentials, believed to be originating predominantly from large diameter, fast conducting axons directly responsible for volitional movements within the CSTs, is initiated. This traveling wave of action potentials can be recorded from the spinal cord directly. To distinguish it from other indirect (I) responses, the direct response has been termed the D-wave (Fig. 13.2).

A description of D-wave characteristics and technical aspects of D-wave monitoring and interpretation are described later in the chapter. When the action potentials contributing to the D-wave descending the CST arrive at the respective synaptic targets on the lower motor neurons in the spinal cord they facilitate depolarization. Lower motor neurons are large and have high capacitance; therefore, they require coincident and repetitive excitatory synaptic events to move their membrane potential above the threshold for firing their own action potentials. For this reason, a single electrical stimulus in the proximal motor pathway, while sufficient to initiate a D-wave, is normally insufficient to trans-synaptically generate an action potential in the lower motor neuron. Therefore, to elicit muscle MEPs we employ a train stimulus paradigm. This results in a rapid succession of D-waves, one for each stimulus pulse in the train (and possibly I-waves, described below), arriving at the lower motor neuron, allowing for temporal summation of excitatory inputs.

At an appropriate stimulus train frequency, the corresponding train of D-waves are superior to a single one at raising the membrane potential of the alpha motor neuron above its threshold, driving it to fire its own action potential and activate the respective muscle fibers. The myogenic motor evoked response obtained when a single motor neuron fires an action potential is a motor unit

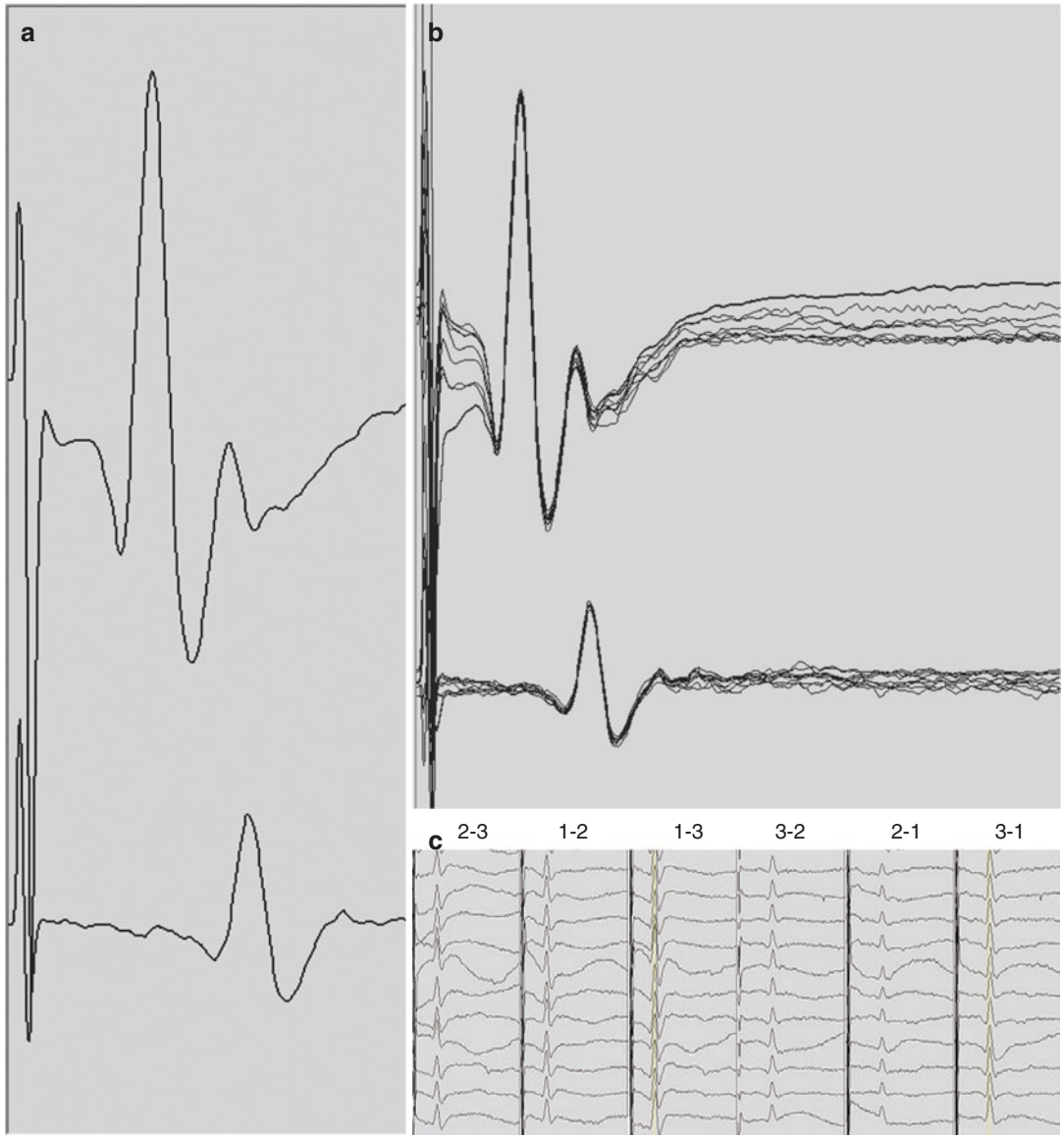

Fig. 13.2 D-waves. (**a**) D-waves recorded in surgery for a T2 hemangioblastoma from a 3-contact, spinal electrode placed rostral to the lesion (top trace) and caudal to the lesion (bottom trace). D-waves in this panel were obtained with the 1-3 and 3-1 montages which typically produce the largest responses. The latency of the peak of the response is 3.2 and 5.3 msec, and, the amplitude measured from the peak to the base of the trailing trough is 103 μV and 34 μV for the rostral and caudal recordings, respectively. (**b**) Overlay of 10 consecutive D-waves recorded in the same patient. (**c**) A selection of the summary of the D-waves. The recording montages are indicated above each column. The three columns on the left are recorded from the rostral electrode while the three columns on the right from the caudal electrode. Display gains were adjusted for clarity and may not be the same across montages

potential (MUP), whereas that obtained when two or more motor neurons fire is a compound muscle action potential (CMAP). It is important to note that muscle MEPs (see below) are sometimes difficult to elicit particularly with transcranial stimulation. In general, it is at and above the level of the alpha motor neuron in the spinal cord that we see neurophysiologic complexity in the

ability to activate the motor pathway and generate muscle MEP responses.

Transcranial Motor Evoked Potentials

MEPs for intraoperative spinal cord monitoring are initiated by transcranial electrical activation of the motor cortex and descending motor fibers and are therefore called transcranial motor evoked potentials (TcMEPs). Subdermal needle electrodes, often of corkscrew design, are placed in the scalp over the approximate location of the primary motor cortex. This may either be at the 10–20 system-derived positions of C3, C4, C1, or C2 or slightly anterior to each of these positions (the so-called "M" locations). Be prepared to incorporate electrodes along the Z line (down the midline) at the respective positions of 1 cm posterior to, and 6 cm anterior to, CZ, so-called CZ minus and CZ 6 cm, respectively. The stimulus montage of C1–C2 is a good choice as an activation site for TcMEP in IMSCT surgery, and the alternate montages of C3–C4 and CZ minus–CZ 6 cm are incorporated as needed. The more medial the montage, the greater the selectivity of activation of the fibers of the lower extremity, with the midline stimulus montage resulting in the strictest focus on the lower extremities. Placing stimulating electrodes with such a lower-extremity focus may possibly cause optimal upper extremity responses to be sacrificed. The objective of medially derived montages is primarily to reduce otherwise unmanageable patient movement during TcMEP monitoring. It is secondarily to reduce the incidence of bite injuries of the tongue and mouth, an undesirable outcome of the transcranial stimulation. Transcranial stimulation is not specific for the CST and also results in corticobulbar activation and/or local depolarization of the temporalis muscles both of which cause jaw clenching. Always work closely with the anesthesiology team to incorporate an intraoral bite block(s) to protect the patient from bite injuries. Stimulation through C3-C4 appears to impose the greatest risk in this regard.

For TcMEP, activation of the motor pathway favors the side of the brain under the anode and, thus, the muscles of the hemi-body opposite the anode. An optimized stimulus selectively activates the motor pathway for only the hemi-body opposite the anode. For example, employing C3 as the anode, one would expect right limb muscle responses, and vice versa for C4. However, that lateral specificity of muscle responses during IMSCT surgery is less important than obtaining reliable responses in the important distal muscles. Furthermore, I recommend recording from both sides of the body with each stimulus polarity. This helps the surgical neurophysiologist to capture responses even if the cathodic stimulus generates them, and furthermore prevents congenital non-decussating motor pathways from going undetected, which would negatively impact TcMEP interpretation otherwise. Stimulus parameters such as voltage/current intensity, pulse duration, pulses per train and interpulse interval, and stimulation delivery approaches such as double trains and repetitive, "build-up"–style stimulus delivery are all important contributing factors to optimized activation for TcMEP. In general, the "sicker" the spinal cord the higher the required intensity, pulse duration, number of pulses per train and interstimulus interval and the more likely it will require double trains and repetitive stimulation.

TcMEPs are normally large amplitude, high-frequency, bi- or multiphasic responses and their complexity is defined by the number of undulations as well as the overall duration of the waveform. The complexity and duration are in part related to the number of pulses in the transcranial stimulus, such that longer stimulus trains typically result in more complex and longer TcMEP responses. TcMEP response amplitude is determined as the absolute difference between the largest negative deflection and the largest positive deflection (peak to trough, or vice versa). In general, the latency of the TcMEP response, measured at the point of take-off of the first deflection, depends on the distance from the stimulus site and the distance from the spinal cord, so distal limb muscles have longer latencies than proximal muscles of the same limb. Determining the absolute latency of TcMEP responses during IONM is difficult because it is not known which pulse in the stimulus train is responsible for initiating the response unless the

number of pulses in the train is decreased to the point at which the response disappears. This is not a common practice in the operating room, since the absolute latency of TcMEP responses is much less critical to their application and interpretation. TcMEP responses are usually obtained from a one stimulus–one response approach and not normally averaged. In the case of irreconcilable noise, TcMEP responses may be averaged over a few consecutive trials. It is important to keep in mind that TcMEP responses inherently vary from trial to trial.

TcMEP responses are obtained from intramuscular or subdermal needle electrodes placed in or near the belly of the muscles of interest. Since TcMEPs are large, high-frequency responses, a LFF of 10–100 Hz, a HFF of 1500–3000 Hz are appropriate, and a high amplifier sensitivity of 500–3000 μV/Div is necessary to avoid clipping of the waveform which would make amplitudes uninterpretable. Start with an acquisition sweep of 100 msec and consider stretching this acquisition to be able to capture lesion induced delayed responses, particularly for distal muscle groups. Display gain should be initially set at 50–100 μV/Div in order to be able to resolve small responses and adjustments to optimize visibility are often warranted. Tracking the display gains is important particularly when TcMEP data changes occur.

A wide distribution of muscle recording sites is recommended. Proximal and distal muscle groups of the lower extremity such as quadriceps, tibialis anterior and foot muscles are recommended in all cases. Anal sphincter recordings may be included as well. For cervical lesions, segmental and suprasegmental muscles should be included. Proximal "control" muscles should be included whenever possible.

Myelogenic Motor Evoked Potentials: D-Waves

D-waves may be elicited by electrical stimulation delivered directly to the descending CST fibers in the spinal cord or in the brain [26–28]. In general, direct stimulation like this is used for mapping and localization. For monitoring D-waves during IMSCT surgery the most common method of activation is transcranial stimulation similar to that employed for TcMEP: electrical pulses delivered to scalp electrodes strategically placed near the motor cortex.

There are important differences between transcranial activation of the motor pathway for TcMEP recording and that for D-wave recording. To obtain D-waves we employ a stimulus of 50–500 μsec (or more) as a single pulse, rather than a train of pulses, since the lower motor neuron and its dependence on temporal summation are excluded during D-wave recording. As a result, patient movement is reduced or eliminated, permitting nearly continuous sampling of D-waves throughout the time the spinal electrode(s) is/are in place. The stimulus for eliciting a D-wave is delivered in such a manner as to obtain responses that correspond to simultaneous activation of both the left and right CST to capture the entire motor axis. To increase the likelihood of this, the C3–C4 scalp electrode positions are favorable, although the other transcranial stimulating electrode positions are also useful and maintain the benefits of focal activation. These more medially located stimulation sites are of greater use in thoracic IMSCT surgery.

For D-wave monitoring, the intensity of the stimulus must be appropriate for simultaneous activation of bilateral CSTs. The stimulus intensity is ramped until the observation of a maximum amplitude response, which suggests bilateral pathways are recruited. The intensity is further increased until a leftward shift in D-wave latency is detected (Fig. 13.3). The intensity just below that which generated the shift in latency at maximum response amplitude is employed for D-wave monitoring. The leftward shift results from deeper activation of the pathway. As the transcranial stimulus intensity is increased, the stimulus-dependent electric field generated under the anode extends across the brain to recruit the contralateral CST. Additional increases in the stimulus intensity then drive the current/electric field deeper into the brain. Consequently, the leading edge of the electric field generated by the stimulus and, therefore, the site of activation of the CSTs, is now more distal and closer to the

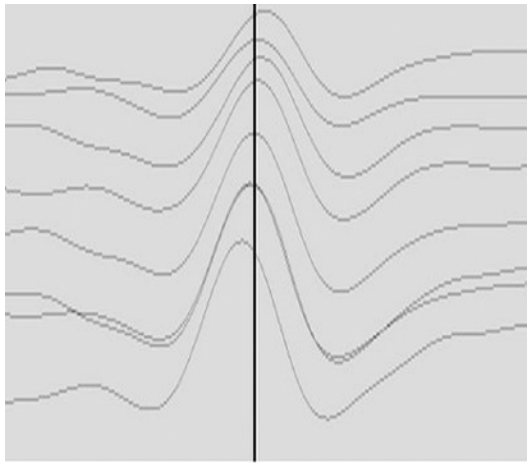

Fig. 13.3 D-waves at increasing stimulus intensity. D-waves obtained during surgery for C3-6 IMSCT at increasing stimulus intensity from low at the top to higher at the bottom. A time marker is indicated for reference. Note, the D-wave amplitude increases, and the latency decreases as the stimulus is increased until reaching a maximum amplitude at a similar latency (overlaid traces). Additional increases in stimulus result in no further increase in amplitude but a decrease in latency

recording electrode in the spine. This results in the shorter latency described above. Thus, at a stimulus intensity just below that which produces this leftward shift and a maximal response amplitude, it is presumed that bilateral CSTs are maximally activated. Independent left and right D-waves elicited by anodal stimulation of the right and left scalp, respectively, are possible but methods to validate confinement of the activation to one side of the motor axis are lacking.

Unlike TcMEPs which are typically stored after a single trial, D-waves may be averaged. Averaging can help to resolve a poorly formed, small or artifact or noise-contaminated D-wave. The spinal electrode contacts are often of moderate impedance and consequently invite noise, so averaging is an important tool for the surgical neurophysiologist. The number of trials per average depends on the signal-to-noise ratio, with better ratios favoring fewer trials per average, possibly as few as one or two trials. D-wave recordings may also be confounded by large stimulus artifacts. With an optimized stimulus (see above) either stimulus polarity should produce monitorable D-waves. Nevertheless, alternating the stimulus polarity between successive trials for an equal number of trials per polarity before collecting an averaged response is an effective way of canceling the stimulus artifact and of improving the measurability of the collected D-wave.

D-waves are high-frequency, large amplitude waveforms. A LFF of 0.2–2 Hz, a HFF of 1500–3000 Hz, and a starting amplifier sensitivity of 20 μV/Div are appropriate. Pinching the LFF to 30–100 may help manage artifact but phase shifting must be considered. D-waves are short latency waveforms requiring concomitantly brief 10–30 msec acquisition sweeps. The display gain is set to 20 μV/Div and the display sweep matches or is longer than the acquisition sweep. When determining the appropriate stimulus intensity, the display sweep may temporarily be decreased to see greater detail of the small latency shift described above.

D-waves are recorded as near field potentials using a spinal electrode that is inserted in the epidural or subdural space by the surgeon (see Fig. 13.1). To facilitate the placement of the electrode, and to optimize contact between the electrode and the tissue, it is recommended that the surgeon irrigates with warm saline as the spinal electrode is inserted. One spinal electrode is placed caudal (distal) to the site of the lesion as the source of the monitored D-wave, and one rostral (proximal) to the site of the lesion as a control whenever possible.

The recording channels for these electrodes depend on their orientation and the number of contacts. Bipolar montages are preferred to take advantage of the differential amplifier's ability to reject common mode noise. Commercially available spinal electrodes come with either two or three 1.3 mm contacts approximately 1.5 cm apart center to center. Two to three centimeter interelectrode distance is reported to be optimal. The electrode contacts are numbered distal to proximal. In order to have the negativity of the D-wave represented as an upward deflection, the active recording channel must be the more proximal contact. Therefore, if using a three-contact spinal electrode, the caudal electrode recording

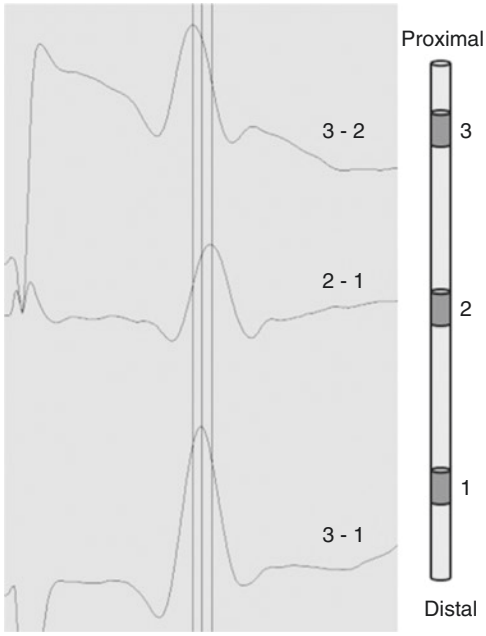

Fig. 13.4 Varying D-wave characteristics at epidural spinal electrode contacts. D-waves obtained from a three-contact epidural spinal electrode using three different bipolar recording montages. Each montage produces a D-wave of different amplitude and latency. A schematic of the epidural electrode with the three contacts is presented on the right. The montages used for recording these D-waves are 3-2 (top trace), 2-1 (middle trace) and 3-1 (lower trace)

montages are (active input to reference input) 3-1, 3-2, and 2-1, whereas, the rostral electrode recording montages are 1-3, 2-3, and 1-2. Since the difference in electrophysiological potentials is being amplified, the montages that include contacts that are farther from each other on the spinal electrode (e.g., 3-1 or 1-3) produce the largest responses due to a reduction in the common mode cancellation of signal that tends to occur between the more closely spaced recording sites (3-2, 2-1 or 1-2, 2-3, Fig. 13.4).

In cases where one of the contacts demonstrates poor impedance, then a referential montage may be employed by adding an electrode outside the epidural space as the reference. This montage is unfavorable as it lends to poorly resolved and noise-contaminated recordings since the recording and reference electrodes have different noise detection. Additionally, the shape of the observed D-wave would not match that observed by using a bipolar montage making it difficult to reconcile with the pattern we expect for D-waves (we are, after all, pattern recognition machines).

The D-wave can be recognized by its characteristic shape and latency. D-wave morphology, when recorded extracellularly using a bipolar montage like that described above, is a large negativity (upward deflection) that is bounded by smaller positivity (see Fig. 13.2). This is common for traveling waves recorded from nerves or tracts. The current loops that allow for axonal conduction and repolarization create these brief periods of preceding and trailing positivity surrounding the large negative deflection of the D-wave. Note, at high stimulus intensities the D-wave may bifurcate or trifurcate.

As a traveling wave, the latency of the D-wave depends on the distance from the activation site. Thus, even the small distance between contacts in the epidural spinal electrode is sufficient, and necessary, to see differences in the recorded latencies of the D-wave (see Fig. 13.4). Furthermore, D-waves at lower spinal levels will have relatively longer latency and D-wave latency increases with near-linearity from the mid-cervical levels down. Following transcranial stimulation, D-waves recorded in the cervical spine may appear at a latency of only a few msec whereas those recorded at the lower thoracic spine may appear at 10's of milliseconds. The short latency of cervical D-waves makes them technically challenging to resolve, as they are often obscured or confounded by an artifact from the stimulus. Averaging responses obtained from alternate stimulus polarities helps to mathematically decrease the stimulus artifact as described above.

The amplitude of the D-wave is directly related to the number of contributing axons. D-waves recorded at higher spinal levels tend to have larger amplitudes than those recorded at lower levels in the same patient since the number of CST fibers is highest in the cervical spinal cord and decreases progressively craniocaudally down the spinal cord. This defines thoracic spinal level 10 as the lower limit of the spine at and above which D-waves can reliably be recorded.

In most patients, D-waves are not reliably obtained at and below the conus, because the number of CST fibers there is below a recordable number.

D-waves are typically brief potentials lasting only a few msec in duration. Complicating their identification, occasionally D-waves spread or disperse due to variability in the conduction velocities and desynchronization of the action potentials across the population of the contributing fibers, particularly when there is an impediment to conduction such as a lesion. Some patients will exhibit dispersion that renders D-waves unrecordable; nevertheless, conduction in the CST is sufficient to permit recording of TcMEP following train stimulation. For example, TcMEP responses are obtainable in infants 18 months and younger but they typically have unrecordable D-waves presumably because immature myelination causes too much dispersion.

When stimulating the proximal motor pathway at high intensities or in an awake or lightly anesthetized patient, a single or a series of waves with D-wave-like morphology may follow the D-wave. These are the so-called indirect, or I-waves, which are believed to derive from the activation of intracortical motor circuits. Their activation results in additional coordinated volleys of action potentials descending the CSTs. I-waves are not a good indicator of functional continuity of the motor pathway and are not used in monitoring. The confounding contribution of I-waves may be reduced by increasing anesthesia or decreasing the stimulus.

Despite D-waves being initiated by a single pulse, muscles may still respond and cause muscle artifact at the spinal electrode. Muscle artifact, which is discernible by its later appearance, broader profile, and often large amplitude, may be seen trailing the D-wave (Fig. 13.5). Since the D-wave potential is neurogenic, suspicion of muscle artifact can be validated by giving a small dose of relaxant. Taking appropriate steps like decreasing the stimulus, increasing anesthesia, or adding a low-dose infusion of relaxant may be helpful if resolving the D-wave from muscle artifact is difficult. Keep in mind that, while D-waves are highly resistant to anesthetic type and concentration, including relaxants, intraoperative changes in anesthesia will have secondary, and potentially profound, effects on the other evoked potentials such as SSEP and TcMEP.

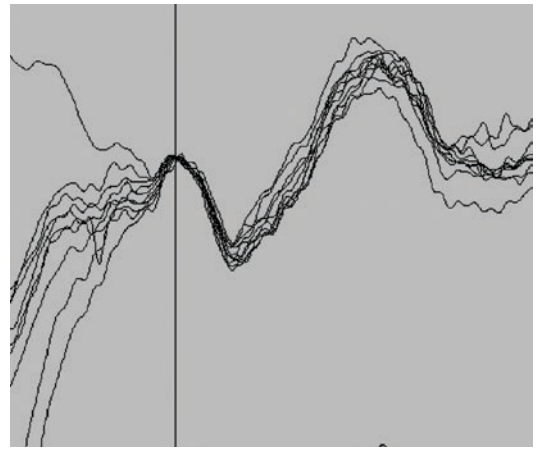

Fig. 13.5 Epidurally recorded muscle artifact. Overlay of 10 consecutive trials showing a poorly formed D-wave (time marker) at a latency of approximately 8 msec, with a large trailing negative deflection likely to be muscle artifact, recorded just below spinal level T8 during surgery for ependymoma

Electromyography

For an in-depth view of EMG, I recommend the reader review Chap. 8. EMG is the recording of the bioelectric activity of muscles as an indicator of neuromuscular activation. EMG is normally quiescent and deflections from the low-level background activity are indicators of perturbation of the innervating nerve, root, or tract. Intramuscular or subdermal needle electrodes are placed in or near the belly of the muscles of interest. Bipolar montages are preferred to optimize common mode cancellation of noise but referential montages are applicable as well. Acquisition sweep is set to 50–500 msec/Div with the objectives being to simultaneously sample enough time per sweep while also being able to resolve details of the EMG responses. Recordings are free-running sweeps taken with filters set at 10–3000/5000 Hz and an amplifier sensitivity of 500–2000 μV/Div.

While the sensory and motor evoked potentials emphasized above serve as the focus of the IONM regime applied for protection of the long

tracts of the spinal cord during IMSCT surgery, it is important to include EMG as well. In the case of IMSCT surgery, the descending CSTs are at risk of direct mechanical perturbation or trauma. Mechanical perturbation of spinal tracts can initiate volleys of action potentials in the CST that trans-synaptically activate lower motor neurons. Their activation is subsequently detected as sustained discharges or trains of free-running EMG. Whether this EMG activity is an indication of impending decrement in TcMEP or motor function remains to be elucidated. Skinner et al. [8] reported that EMG from tibialis anterior and abductor hallucis recorded at amplifier sensitivity of 20 μV/Div and filters set from 30 Hz–2000 Hz was beneficial in monitoring during IMSCT surgery, and even that EMG events precede and provide warning signs of changes in TcMEPs, findings also recognized in the study by Baeesa et al. [29]. I encourage surgical neurophysiologists to include EMG for the same muscle groups being monitored by TcMEP in their strategy for monitoring during IMSCT surgery as personal experience (unpublished observations) corroborates that of Skinner et al. and Baeesa et al. [8, 29].

Spinal Cord Mapping

Spinal cord mapping includes methods for minimizing neural injury caused by both the surgical entry into the spinal cord and while developing the trajectory to the tumor. Others aim to localize, characterize, or determine the approximate distance from the CSTs [9, 20, 30]. Spinal cord mapping may be incorporated into the IONM strategy during surgery for non-tumor spinal cord lesions and malformations as well. For IMSCTs, the mass effect of space-occupying spinal cord lesions distorts the structure of the spinal cord and/or obscures normal anatomical landmarks, making it difficult for the surgeon to determine the safest entry point into the spinal cord using visual cues alone. Once inside the cord, the margins between a lesion, particularly those of infiltrative subtypes, and normal tissue are difficult to distinguish visually. To this end, mapping of the surface of the dorsal columns and intramedullary mapping of the CSTs has been incorporated in the IONM strategy during IMSCT surgery. It is important to note that intraoperative spinal cord mapping methods, in general, are not a replacement for spinal cord monitoring methods.

Mapping the surface of the spinal cord during IMSCT surgery reduces the incidence of postoperative neurologic deficits [9, 10] and, as such, has emerged as an important addition to the IONM regime therein. The physiologic map determined intraoperatively is combined with imaging and/or navigation results, and with the appearance of the tissue to identify the safest entry point and trajectory into the spinal cord. Access to the inside of the spinal cord during IMSCT surgery is commonly through midline myelotomy at the posterior median septum down the sulcus between the left and right gracile fasciculi. Identifying this septum is critical in this stage of the surgery.

Dorsal Column Mapping

Dorsal column mapping, as the method has been aptly named, has benefitted from some recent methodologic refinements. There are essentially two approaches to dorsal column mapping. In the first, a peripheral nerve is stimulated and potentials in the spinal cord are recorded directly. In the second, the spinal cord is stimulated directly and potentials in distal nerves or the brain via scalp electrodes are recorded. The methods are, nevertheless, based on the same principle. The left and right gracile fasciculi are discrete, parallel (normally) spinal cord pathways that can be readily distinguished physiologically.

Recording from the Spinal Cord

In one method of dorsal column mapping, a specialized, micro-grid electrode is placed on the dorsal surface of the spinal cord [10, 13, 31, 32]. Tibial nerve spinal responses are elicited by standard SSEP stimulation techniques. Responses resulting from independent stimulation of each of the tibial nerves (the median nerves can be used as well, although less commonly and for different mapping information [31]) are recorded directly from the spinal cord,

and the gradient of response amplitudes across grid contacts is compared. The grid is laid perpendicular to the long axis of the spinal cord and each contact of the grid contributes to a separate referential montage with the reference electrode placed in the surrounding tissue preferentially at a location equidistant from the micro-grid contacts. Responses are obtained at filters set to LFF of 20–50 Hz and HFF of 1700–2000 Hz. The latency and absolute amplitude of the responses depends on the level of the spinal cord at which the recordings are taken. The grid contact producing the most robust/largest response is localized over the respective gracile fasciculus closest to the midline. The rationale being that the dorsal median septum lies between the contacts that produce the largest responses following stimulation of the left and then the right tibial nerves. Admittedly, the difference between the maximal responses and the others is often subtle and a trained eye is required to interpret them. Furthermore, they are often small responses, inherently variable from trial to trial, tend to be easily contaminated by noise and therefore take time to average the high number of trials required to overcome the poor signal-to-noise ratio. Finally, the micro-grids used for recording are normally developed in house or are expensive if purchased commercially and are challenging to keep stably in place on the spinal cord throughout the required recording period.

Stimulating the Spinal Cord

Stimulation of the spinal cord via two adjacent contacts of a micro-grid placed perpendicular to the long axis of the spinal cord elicits sensory responses at scalp electrodes [33]. Recording from the CP3–CP4 montage, as you would for SSEPs generated from nerves in the limbs, produces averaged scalp potentials of opposite polarity when the right versus the left side of the spinal cord is stimulated. This approach is aptly named the phase reversal method. The stimulus employed is 300 μsec, 0.2 mA constant current pulses delivered at 3.17 Hz at two adjacent contacts on the micro-grid. It was postulated that a "null point" between the electrodes that activated the left and right sides of the cord, corresponding to the anatomical location of the dorsal median septum, would produce cancellation of the potentials at the CP3–CP4 channel as there would be equal activation of the right and left gracile fasciculi simultaneously. The method was later adapted further, employing the same stimulus and recording parameters, but including a handheld bipolar stimulation probe rather than the micro-grid [34] (Figs. 13.6 and 13.7).

These authors demonstrate phase reversal of scalp potentials as the stimulus is moved across the spinal cord and also a point at which the scalp potentials flatten, which they describe as corresponding to the location of the dorsal median septum.

The dorsal median septum can be further elucidated by the inclusion of peripheral recordings such as at Erb's point, the median and ulnar nerves, the popliteal fossa and/or the tibial nerve [9, 35]. In one method of dorsal column mapping focused on recording from the tibial nerve at the ankle, the stimulus consists of 3–8 mA, 200 μsec constant current pulses delivered at 9.1 Hz through a handheld bipolar stimulator with 2–3 mm separation of the tips [35]. The cathode is oriented inferiorly. Subdermal needle electrodes placed behind the medial malleolus over the distal tibial nerve capture antidromic potentials generated at the spinal cord using LFF and HFF filters set to 30 and 300 Hz, respectively. Methodologic advances include recording from Erb's point, the median and ulnar nerves at the wrist and elbow in addition to the popliteal fossa, with stimuli of 2 mA, 100 μsec constant current pulses delivered at 2.1 Hz through a concentric bipolar handheld stimulator [9]. Again, antidromic potentials elicited at the spinal cord are captured using subdermal needle electrodes placed over the targets using LFF of 30 Hz and HFF of 500 Hz. These researchers suggest, for cervical lesions, proximal recordings of the median and ulnar nerves at the elbow are preferred over recordings at the wrist and that in all cases they met with limited success obtaining potentials at the popliteal fossa. For each of these methods, the laterality of the responses corresponds to the side of the spinal cord stimulated. Stimulation near the dorsal median septum results in either

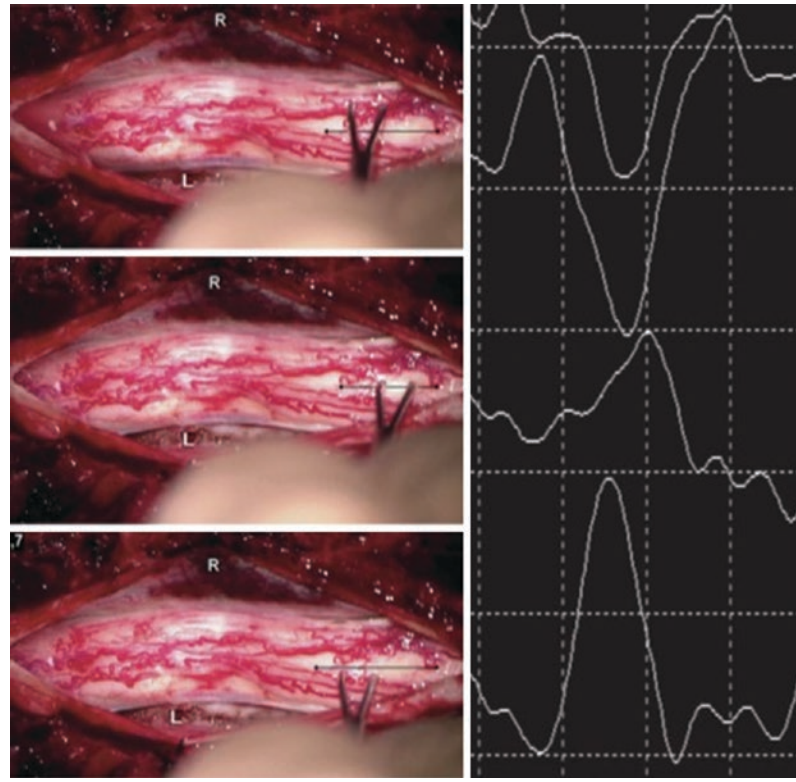

Fig. 13.6 Dorsal column mapping by the phase reversal method. Left panels are intraoperative photographs of the spinal cord showing the simulation method incorporating a side-by-side bipolar probe on the right (top), at the midline (middle) and on the left (bottom) of the spinal cord. The right panel shows corresponding scalp recordings at CP3-CP4 that are opposite polarity for the right and left sides and flattened at the midline. (Modified with permission from Nair et al. [34]; by permission of Oxford University Press)

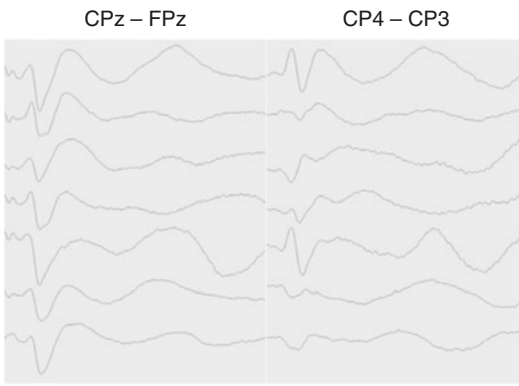

Fig. 13.7 Dorsal column mapping by the phase reversal method. The spinal cord was stimulated at 1 mA, 200 μsec pulse duration, 2.79 Hz through a handheld monopolar probe. Recording channels are indicated at the top of each column. From top to bottom, the scalp potentials at CP4-CP3 indicate that left cord, midline, right cord, midline, left cord and then two trials at the midline stimulation occurred

bilateral peripheral responses or no responses, depending on whether the stimulus delivered at the dorsal midline recruits dorsal column fibers on both sides of the cord or is lost in the sulcus.

Peripheral recordings during dorsal column mapping are particularly helpful in patients who have problematic or unresolvable tibial nerve cortical SSEPs. Furthermore, combining dorsal column mapping methods may provide enhanced applicability, accuracy, and reliability. Figure 13.8 depicts dorsal column mapping results obtained from a 6-year old with a mid-cervical ependymoma. Stimulation consisted of 200 μsec, 1 mA constant current pulses delivered at 2.67 Hz through a handheld, side-by-side bipolar probe with the tips separated by 0.3–0.5 cm. The tips of the stimulator were oriented long-wise, but the polarity of the stimulator tips was not tracked; therefore, it is unknown if the cathode was superior or inferior. Figure 13.8 depicts simultaneous responses at scalp, popliteal fossa and muscles recording sites obtained from direct stimulation of the spinal cord and shows that (1) the phase of the scalp response is consistent with the laterality of the responses at popliteal fossa and muscle recording sites and (2) the "null point" scalp responses are consistent with bilateral responses

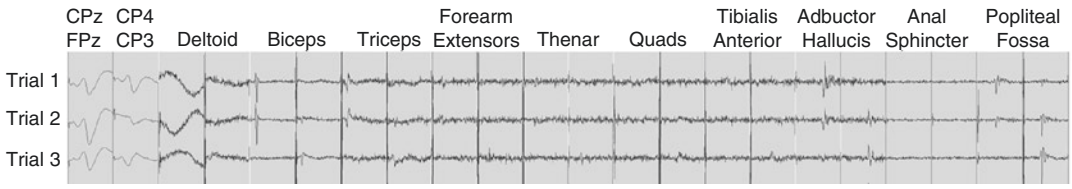

Fig. 13.8 Dorsal column mapping combining phase reversal at the scalp with peripheral nerve and muscle recordings obtained from a 6-year old with a mid-cervical ependymoma. The spinal cord was stimulated at 1 mA, 200 μsec pulse duration, 2.79 Hz, with a handheld, side-by-side, bipolar probe at approximately spinal level C6. The scalp montages and recording sites are indicated at the top of each column. The left two columns show scalp recordings at CPz-FPz and CP4-CP3. The remaining columns show alternating left and right side recordings. Columns three through 20 show muscle recordings. The two columns on the far right show popliteal fossa recordings. From top to bottom, the responses in each row indicate left side, midline then right side spinal cord stimulation

at the popliteal fossa and muscle recording sites. This combination of methods resulted in quick and accurate localization of the dorsal median septum in this patient. Future research regarding refinements and outcomes of this method will be beneficial. It is important to note that, in this case, the responses obtained at muscle recording sites were small and many of them, particularly of the upper arm, were short latency and duration. Furthermore, the most robust responses appeared at the popliteal fossa recording sites and the most robust responses at muscle recording sites appeared at the foot and secondarily in the proximal arm. Despite the stimulator being placed on the dorsal columns, the precise activation site of the observed muscle responses may either be the dorsal columns or the CST directly. A method for distinguishing between the activation site is described below.

CST Mapping

The CST can be localized via "collision studies"— recording a caudal D-wave elicited by transcranial stimulation of the proximal motor pathway and pairing that with direct spinal cord stimulation of the distal motor pathway [32]. Distal stimulation using a handheld probe delivering 2 mA cathodal stimulus pulses in proximity to fibers of the CST results in their recruitment and retrogradely transmitted action potentials in the CST fibers. These retrograde action potentials interfere, or "collide," with the transcranially elicited action potentials anterogradely descending the CST. According to these methods, a reduction in amplitude of the D-wave recorded caudally indicates a collision has taken place and is interpreted as meaning the stimulation is localized to or near the CST.

Responses in muscles are elicited by direct CST stimulation when employing stimulus trains [35, 36]. Free-running EMG responses of the tibialis anterior and abductor hallucis muscles are recorded at filters set to LFF of 30 Hz and HFF of 1000 Hz. Responses are elicited with constant current, 1 mA and higher, 1 msec pulses delivered at 60 Hz through a handheld bipolar probe the tips of which are separated by 0.5 cm. Stimuli are delivered for 1 sec. In another method, the location of the tumor-tissue interface and the precise proximity of specific contents of the CST can be elucidated in greater detail by micro-stimulation, wherein a handheld concentric bipolar stimulator is employed to deliver 1 msec, biphasic current pulses of 0.1–1.0 mA at 60.11 Hz [37]. Recordings are obtained using filters of 30 and 500 Hz for LFF and HFF, respectively, and an amplifier sensitivity of 200 μV/Div at the thenar-hypothenar hand muscles, the tibialis anterior, extensor hallucis longus, medial gastrocnemius, and the abductor hallucis muscles of the lower extremity. The data from this micro-stimulation study emphasize the need for a broad distribution of muscle recording sites when monitoring for IMSCT surgery.

Recently, Bazilar et al. [38] described a method of transforming the tip of a CUSA into an electrical stimulator delivering 0.5–2 mA, cathodal, constant current, stimulus trains of three 200 μsec long pulses per train, repeated at 1.2 Hz. They report continuous "mapping" of the CST by observing MEPs while working on the tumor since they are able to stimulate repeatedly as they are resecting with the electrified CUSA. While similar to mapping methods, what these authors describe may lead to a new monitoring method during IMSCT surgery. Additional data on the applicability and interpretation of this method are needed.

In methods that employ direct stimulation of the CST with detection of muscle responses, the site of activation of the pathway is unclear. Muscle responses are known to be elicited from stimulation of CST fibers directly, but also indirectly from activation of the dorsal columns. Activating the spinal cord with a double train stimulation protocol with a 60 msec intertrain interval can distinguish the source of activation of muscle responses [39]. Trains of 0.3–5.0 mA constant current, cathodal stimuli of three to five 500 μsec pulses per train, with an interpulse interval of 2–4 msec, are delivered twice consecutively with 60 msec between each train through a concentric bipolar handheld stimulator. Muscle responses are recorded at filters of 10 Hz and 2000 Hz for the LFF and HFF, respectively, in the deltoid, biceps, triceps, extensor digitorum, abductor pollicis brevis, quadriceps, tibialis anterior, gastrocnemius, and abductor hallucis. Since the CST fibers have a shorter refractory period than sensory fibers (such as those of the dorsal columns) direct activation of the CST results in similar muscle responses from each of the two stimulus trains but disparate muscle responses when the dorsal column is activated (Fig. 13.9).

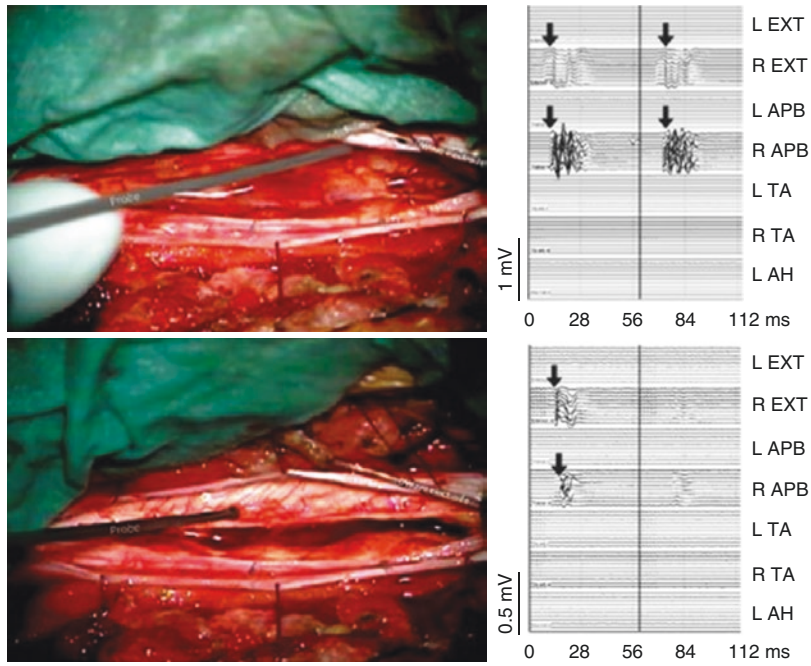

Fig. 13.9 Spinal cord mapping using double trains to distinguish the CST from the dorsal columns as the activation site of muscle response. Left panels are intraoperative photographs of the spinal cord showing the double train simulation method incorporating a concentric bipolar probe on the right corticospinal tract (top) and on the dorsal columns (bottom) of the spinal cord. Right panels depict corresponding muscle recordings from train one (left column) and train two (right column) showing consistent muscle responses (arrows) elicited by both of the trains when activating the corticospinal tract (top) in contrast to disparate responses between the two trains when activating the dorsal columns (bottom). (Modified with permission from Deletis et al. [39], copyright 2018, with permission from BMJ Publishing Group Ltd)

Anesthesia

Anesthesia for monitoring SSEPs, TcMEPs, and EMG has been described in detail in other sections of this text (Chap. 5). Constant, stable anesthesia is critical for the most effective delivery of IONM. This is achieved through steady-state infusion at a constant rate avoiding bolus administration or limiting boluses to induction and select stages of the surgery (like exposure). The surgical neurophysiologist should track closely the anesthetics being used, the infusion rates and boluses administered and incorporate electroencephalography (EEG) since it is an indispensable tool for evaluating the relative depth of the patient throughout the procedure. Optimal anesthesia is delivered intravenously with moderate infusion rates of propofol at 50–200 μg/kg/min and narcotics such as fentanyl around 1 μg/kg/hr. or remifentanyl at 0.2–0.5 μg/kg/min. Gas anesthesia should be avoided, as it reduces the "activatability" of the tissue, particularly, motor tissue of TcMEP. In some instances, particularly for neurologically intact patients, halogenated agents administered at ½ MAC or less or nitrous oxide administered at less than 50% is acceptable but not advised and, in instances of mixed anesthesia, would be paired with lower infusion rates of propofol.

In general, low doses of short-acting muscle relaxants are restricted to induction for cases involving TcMEP and EMG, and clearance of the relaxant must be validated through a train of four evaluation of the neuromuscular junction before baselines are obtained. Relaxants block muscle activation aggressively, such that even with 3 of 4 retained twitches up to 75% of the activatable tissue is still chemically blocked. These neuromuscular blocking agents must be incorporated with great care in order for TcMEP and EMG monitoring to be accurate and reliable.

The anesthetic approaches described above are appropriate for D-wave monitoring and spinal cord mapping. D-waves are tolerant of anesthetics, including relaxants, at doses normally administered for IONM. Anesthesia for spinal cord mapping involving scalp recordings and muscle responses should follow standard approaches for anesthesia appropriate for SSEP and EMG monitoring, respectively. Dorsal column mapping methods that incorporate peripheral nerve recordings do not have specific anesthesia requirements, as peripheral responses are largely insensitive to anesthetics including muscle relaxants.

The surgical neurophysiologist should always track closely systemic physiologic variables such as blood pressure, mean arterial pressure, heart rate, oxygenation, and temperature, since these variables directly impact IONM responses and neural responsiveness. This is particularly true during IONM for IMSCT surgery since the interpretation of SSEPs and TcMEPs is intimately related to the state of these variables.

For IMSCTs at high thoracic levels particularly, special consideration should be given relative to blood pressure and heart rate. Autonomic dysreflexia resulting in rapidly spiking blood pressure and/or heart rate caused by manipulation of the spinal cord at these spinal levels may be misconstrued as an emerging patient [40]. It is critical to have a discussion with the anesthesia team prior to surgery to prepare them to treat these events with non-anesthetic drugs and not address them with an additional anesthetic, an increase in infusion rate or a bolus of anesthetic such as propofol, as this will adversely impact the IONM data with the additional consequence of slow recovery.

IONM Data Changes: Warning Criteria

Evaluation of IONM data changes in IMSCT surgery includes several factors:

- The quality of the signal(s) to start
- The pattern of the change(s)
- The circumstances surrounding the change(s) including:
  - Surgical stage
  - Anesthesia composition and levels
  - Physiologic variables
  - The condition of other IONM signals
  - Evidence of signal fade
- The spinal location, spinal levels, and type of the tumor

With these in mind, the neurophysiologist can identify with reasonable accuracy the site of the IONM data change and can discriminate the source as surgical versus positional versus systemic. Additionally, warning criteria for alerting the surgeon to IONM signal changes, based largely on comparison of the state of the current signals to the parameters of baseline signals strategically set at an earlier stage of the surgery, exist. Nevertheless, the surgical neurophysiologist should be attentive to deteriorating IONM signals, as they can happen rapidly in IMSCT surgery, and notify the surgeon at the outset to have the best chance of employing appropriate tissue- and function-preserving interventions. False negatives may result in unexpected postoperative neurologic outcomes, whereas false positives may lead to an abandonment of the tumor resection. IONM interpretation in IMSCT surgery must include a balance of sensitivity and specificity that limits both false negatives, minimizing unanticipated iatrogenic sequelae as well as false positives, thereby preventing suboptimal or incomplete tumor resection.

SSEPs are evaluated at each recording point along the pathway to localize the site of an SSEP data change. Responses are evaluated throughout the procedure for decreases in amplitude or increases in latency relative to a baseline strategically set earlier in the procedure. SSEPs should also be evaluated against a brief recent history of acquired SSEPs to reduce false positives that may arise from the comparison of data acquired long after the setting of an opening baseline. In general, precipitous changes in SSEPs are more concerning than gradual ones. A decrease in amplitude of 50% and/or an increase in latency of 10% have long been the standard warning criteria for SSEP cortical potentials (although there are new perspectives on the effective warning criteria) [21–23]. For many surgeons, it is rare to abort the IMSCT surgery on the basis of isolated SSEP signal changes in the absence of concomitant TcMEP and/or D-wave signal changes.

Like SSEPs, abrupt changes in TcMEP are a greater concern than gradual changes. It is important to note that TcMEP changes often happen rapidly in IMSCT surgery; therefore, TcMEPs need to be sampled frequently in order to anticipate motor changes and to make TcMEPs as effective a tool as possible in both protection as well as prognostication. There are varying views regarding the most effective warning criteria for TcMEP responses, and a body of work suggests the best way to evaluate the risk to motor function in IMSCT surgery is to relate TcMEP responses to the status of the D-wave, whenever possible [41]. Warning criteria for TcMEP fall into three main categories: the absence or presence criteria, activation threshold criteria, and the morphology (particularly percent-reduction) criteria. When evaluating TcMEP using the absence or presence criteria, which is the most documented alarm criteria for TcMEP during IMSCT surgery, an alarm is raised when a previously responsive muscle is now unresponsive [17, 42]. When evaluating TcMEP using the activation threshold criteria, an alarm is raised when there is a 100 V or more increase in the stimulus required to generate TcMEP responses [14, 43]. There are several aspects of TcMEP morphology that are evaluated, including amplitude, which is the most common method, complexity, and duration. When evaluating the TcMEP using an amplitude reduction criterion, an alarm is raised when the TcMEP responses are reduced by 50–80% of the baseline amplitude [6, 44]. When evaluating TcMEP responses using the complexity criterion an alarm is raised when responses become less complex, for example, from multiphasic to biphasic [14]. When evaluating TcMEP responses using a duration criterion an alarm is raised when the duration decreases by approximately 50% [14]. In order to optimally apply complexity and duration criteria to TcMEP the stimulus used to elicit responses should consist of a high number of pulses per train. The results of the complexity criterion and duration criterion methods have not been replicated and more research is required to validate them. In any case, an alarm based on the absence or presence criteria is more likely to warrant a major intervention whereas an alarm based on the other criteria may suitably be addressed with a minor intervention. Finally, improvement of responses that have changed from baseline and the duration of these signal changes are related to

the likelihood of functional preservation and/or the length of time required for functional recovery – the closer the improved responses approximate baseline and the shorter the period during which the responses were altered the better the outcomes. The most effective TcMEP alarm criteria in IMSCT surgery that does not include D-wave monitoring is likely to be one that combines these methods and includes consensus regarding the acceptable postoperative neurological status – is no weakness or transient weakness acceptable? Studies on alarm criteria for TcMEPs in IMSCT typically include permissible levels of transient postoperative weakness that recovers in the hours to months following surgery since the major objective of surgery is clearing the patient of cancer. Some investigators extend the understanding of TcMEP warning criteria and report that the appropriate warning criteria depend on the tumor type or the spinal level [6, 18].

D-waves are normally very stable as long as the stimulus and electrode position remain constant, and there is little evidence that they exhibit fade like that commonly seen for other evoked potentials such as SSEPs and TcMEPs. The most common interpretive parameter of D-waves is amplitude. The important threshold for decreases in D-wave amplitude is 50%, and a D-wave that has decreased below this threshold indicates there will be motor functional changes postoperatively, with full loss of D-wave equating with permanent paralysis [17, 24–27]. The best way of evaluating D-waves is in the context of the results of TcMEPs. If there is loss of TcMEPs with coincident full preservation of the D-wave amplitude, or if there is fully preserved TcMEPs with coincident loss of D-wave, then the motor function is preserved or recovers postoperatively. In the case of loss of TcMEPs with preservation of the D-wave to at least 50% of the baseline amplitude, there will be transient motor functional changes. In the case of loss of TcMEPs and loss or decrease of the D-wave to below 50% of the baseline amplitude there will be long-term or permanent paralysis. Note, in a case of intraoperative decrease of or loss of D-wave with fully preserved TcMEP responses a technical issue should be considered.

The warning criteria for EMG during IMSCT surgery are primarily based on similar warning criteria established for other surgery types, since there has not been a large-scale study of the relationship between patterns of EMG and IMSCT surgical interventions or patient outcomes. Based on one study with a small sample size but an apparent relationship of EMG patterns to motor functional outcomes, the warning criteria include observation of EMG bursts that are coincident with surgical manipulation, prolonged EMG discharges lasting longer than a few seconds and EMG signal that abruptly silences [8]. In all instances of an alarm being raised, TcMEP should be run and muscle responses evaluated based on TcMEP warning criteria and the observed pattern of EMG activity.

Strategies Following IONM Data Changes

In the event an IONM data change exceeding the warning criteria arises during surgery for IMSCT, there are several corrective interventions the surgeon and surgical team may deploy, and these strategies may be (and often are) combined. The first is to pause the surgery. In theory, this allows the nervous system to reset and should last as long as it takes for the IONM data to improve, even as long as 30 minutes.

Irrigation with warm saline is also recommended. A consequence of perturbation of the nervous system is the pooling of ions, particularly potassium, in the extracellular space and the degradation of the normal ion concentration gradients. An abnormal concentration gradient of potassium blocks action potential conduction and results in loss of IONM signals. Irrigation helps to reestablish the appropriate gradients and axonal conduction. At the same time, irrigation helps to clear blood products that are also known to impede nerve conduction.

When the suspected sources of IONM signal loss, usually seen in SSEPs, is retraction on the dorsal surface of the spinal cord, then the surgeon should consider releasing or relaxing the retraction as mentioned above. The surgeon may opt to

simply pause with the reduced retraction, and then reapply retraction after the signals have improved. Improvement in SSEPs in this circumstance often occurs rapidly. Alternatively, the surgeon can release the retraction and extend the myelotomy. This is thought to allow the spinal cord to open more freely, decreasing the retractor-induced mechanical stretch or compression on the dorsal columns when the retractors are reapplied.

Maybe the most common strategy to address IONM data change is to take measures to increase perfusion. This is achieved most simply by pharmacologically increasing the blood pressure/mean arterial pressure, presumably resulting in improved perfusion of the spinal cord. Additionally, the surgeon may directly apply papaverine, a smooth muscle relaxant, that results in vasodilation and consequently improves blood volume to the spinal cord.

Persistent IONM data changes may be addressed with the administration of steroids such as an intravenous dose of 30 mg/kg of methylprednisolone.

Lastly, the surgery may be aborted or deferred until after the patient has recovered and has shown improvement in their neurologic function. If surgery is still indicated, they may return to the operating room at that point.

Conclusion

The goals of surgery for IMSCT are extensive if not complete tumor resection in order to not only limit the progression of the disease, but to rid the patient of cancer, its associated symptoms and risks, and to reduce recurrence. These are paralleled by the goals of preserving the patient's neural function and quality of life. IONM incorporating SSEPs, TcMEP, and D-waves of spinal cord sensory and motor function, and neurophysiologic mapping of spinal cord structures such as the dorsal columns and the CSTs helps the surgeon achieve these goals. Recent advances in the methodology and application of these neurophysiologic tools have made IONM indispensable in the practice of surgery for IMSCTs.

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Review Questions

1. What advantages does monitoring D-waves offer for intramedullary spinal cord surgery?
2. How do D-wave and TcMEP monitoring work together to improve surgical outcome?
3. Describe two techniques for dorsal column mapping and why dorsal column mapping may be performed.
4. How might surgeons respond to changes in spinal cord mapping and monitoring data?

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14 Monitoring Posterior Fossa Craniotomies

Denise A. Birkholz and Scott Francis Davis

Introduction

The base of the skull is divided into three regions: the posterior, middle, and anterior cranial fossae (Fig. 14.1). The posterior fossa is the deepest and largest and is enclosed by the occipital bone. Within the posterior fossa are the brainstem and cerebellum. The brainstem—consisting of the midbrain (mesencephalon), pons, and medulla—contains the nuclei of cranial nerves (CN) III–XII and is responsible for a vital autonomic nervous system function. The brainstem also contains afferent and efferent fiber tracts that connect the brain with the rest of the body. The cerebellum is responsible for movement, balance, and coordination. Due to the complex anatomy and close proximity of these vital structures to each other, the use of intraoperative neuromonitoring (IOM) during posterior skull base surgery can aid the surgeon in identifying neural structures at risk as well as verifying neural integrity once the decompression is complete. This chapter focuses on surgeries for microvascular decompression (MVD), vestibular schwannoma, and Chiari malformation and the modalities used to preserve the neurological function of cranial nerves and brainstem structures during these types of surgeries.

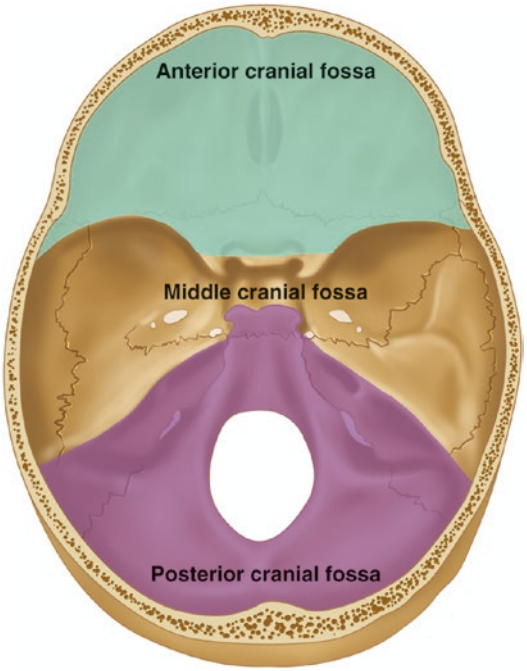

Fig. 14.1 Anterior, middle, and posterior cranial fossae

Microvascular Decompression

MVD is a procedure to relieve symptoms caused by vascular compression of a nerve. When medication does not provide relief, an

D. A. Birkholz
Neuromonitoring Associates, LLC, Las Vegas, NV, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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MVD surgery is an option to treat syndromes such as trigeminal neuralgia, hemifacial spasm, and the less common glossopharyngeal neuralgia (not discussed in this section). To gain access to the offending vessel and the affected nerve, an incision is made behind the ear on the side of the head where the patient feels pain. A portion of the skull is removed and the dura is opened to expose the cerebellum. The cerebellum is moved out of the way, exposing the brainstem. Typically under a microscope, the arachnoid layer is dissected away allowing for visualization of the facial nerve (CNVII), the vestibulocochlear nerve (CNVIII), and finally the trigeminal nerve (CNV). The surgeon places a tiny Teflon sponge between the compressing vessel and the nerve, isolating the nerve from the pulsating effect and pressure of the blood vessel (Fig. 14.2).

During surgery to address cranial neuralgias, surgeons typically opt to monitor the trigeminal nerve (CNV) and the facial nerve (CNVII), using free-running EMG and triggered EMG. The trigeminal nerve is monitored by placing needle electrodes in the masseter or temporalis muscle. Facial nerve monitoring is accomplished by placing electrodes in the muscles of the five main branches of CNVII that control facial expression: temporal, zygomatic, buccal, marginal mandibular, and cervical. EMG monitoring is helpful in locating the cranial nerves and determining adequate decompression. A complication of MVD surgery is ipsilateral hearing loss from injury to the vestibulocochlear nerve. Brainstem auditory evoked potentials (BAEPs) are used to help prevent injury to CNVIII due to traction, ischemia, or cautery. BAEPS are also utilized when there

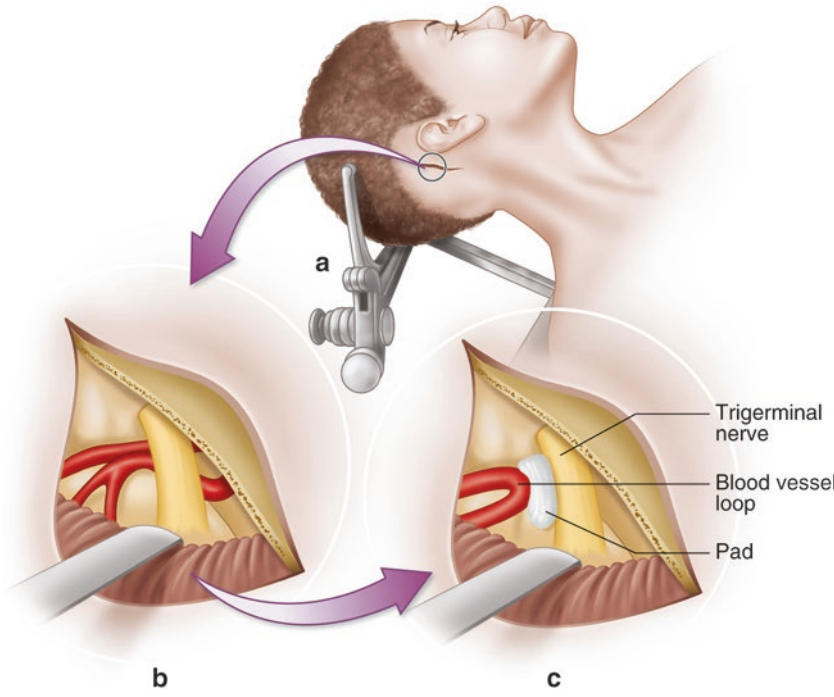

Fig. 14.2 Microvascular decompression. (**a**) Access to the trigeminal or facial nerve is accomplished through a posterior fossa craniotomy. (**b**) The cerebellum is retracted exposing the nerve and the offending blood vessel. (**c**) A Teflon pad is placed between the nerve and vessel, decompressing the nerve

is a risk of brainstem ischemia associated with manipulation of the cerebellum.

Trigeminal neuralgia, also known as *tic douloureux*, is an inflammation of the trigeminal nerve causing extreme pain and muscle spasms in the face. The trigeminal nerve functions in sensing facial touch, pain, and temperature, as well as controlling muscles used for chewing. Attacks of intense, electric shock-like facial pain can occur without warning or be triggered by touching specific areas of the face. The trigeminal nerve has three major branches. The ophthalmic, or upper, branch supplies sensation to most of the scalp, forehead, eye, and eyebrow. The maxillary, or middle, branch passes through the cheek, upper jaw, top lip, teeth and gums, and to the side of the nose. The nerve's mandibular, or lower, branch passes through the lower jaw, teeth, gums, and bottom lip. More than one nerve branch can be affected by the disorder. The superior cerebellar artery (SCA) is the vessel most often responsible for neurovascular compression of the trigeminal nerve root, although other arteries or veins may be the culprit vessels [1]. BAEPs and EMG for CNV and CNVII are typical modalities used for monitoring of MVD to relieve trigeminal neuralgia. The t-EMG response for CNV can easily be confused with CNVII responses. The latency of a t-EMG response from the trigeminal nerve should be around 5 ms, while a facial nerve response is seen around 7 ms when stimulated near the exit point from the brainstem. This should be very easy to remember!

Hemifacial spasm (HFS) is characterized by intermittent, involuntary twitching of the muscles in one side of the face, which lasts from a few seconds to several minutes. Spasms occur spontaneously and without warning. They are often exacerbated by stress or fatigue but can also be triggered by stimuli like sunlight, touch, chewing, and talking. Spasms do not cause pain, but can cause discomfort, impaired vision, social distraction, and embarrassment. HFS is most often caused by a branch of the posterior inferior cerebellar artery (PICA) or anterior inferior cerebellar artery (AICA), pulsating against the facial nerve root as it leaves the brainstem, resulting in hyperactivity of the facial nerve [1, 2]. Similar to the treatment for trigeminal neuralgia, in order to relieve HFS symptoms the facial nerve must be moved away from the offending vasculature.

To adequately monitor the facial nerve, electrodes are placed in muscles corresponding to the extracranial branches that control facial expression. For example, electrodes can be placed in the orbicularis oculi (temporal branch), nasalis (zygomatic branch), orbicularis oris (buccal branch), mentalis (mandibular branch), and if requested, the platysma (cervical branch). Free-running EMG responses in any of these muscles can indicate surgical manipulation [3]. Triggered-EMG responses can assist the surgeon in verifying the degree of decompression of the nerve. In patients with HFS, stimulation of a branch of the facial nerve may result in delayed muscle activity recorded from myotomes of adjacent branches. This is known as a lateral spread response (LSR). Current understanding is that compression of the nerve causes antidromic signals to travel back to the facial nerve nucleus within the brainstem where the nucleus becomes hyperactive and sends signals to all branches, resulting in abnormal facial movements [2–5]. Stimulation of a branch of the facial nerve may have the same effect. For example, stimulating the marginal mandibular branch and seeing a delayed response in the orbicularis oculi is evidence of a lateral spread response (Fig. 14.3). Once the offending vessel is isolated and adequate decompression has been achieved, this abnormal muscle response usually disappears. If it still persists, an additional vessel that was not apparent during visual inspection may be compressing the nerve. Monitoring the lateral spread response decreases the incidence of re-operation.

The close proximity of CNVIII puts hearing at risk during surgery for MVD. BAEPs are monitored during HFS surgery to protect hearing. In addition, BAEPs offer protection against ischemia to the brainstem.

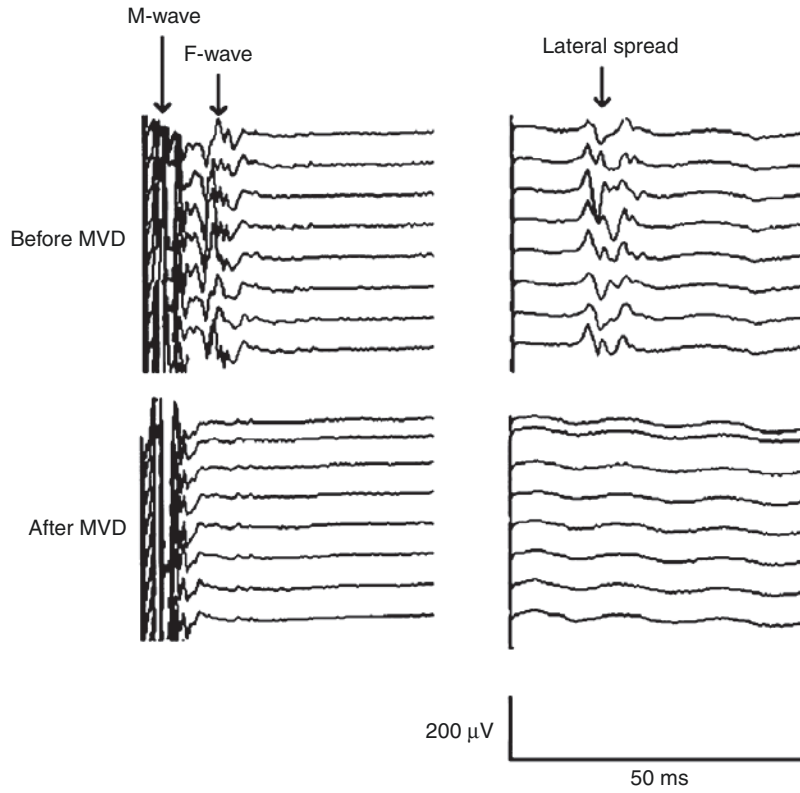

Fig. 14.3 Recordings of LSR and F wave were obtained after direct stimulation of marginal mandibular branch (*left column*) showing LSR to the orbicularis oculi muscle (*right column*). Simultaneous disappearance of the LSR and F wave after MVD was achieved. (Reprinted with permission from Fernández-Conejero et al. [16])

Vestibular Schwannoma

A vestibular schwannoma, also referred to as an acoustic neuroma, is a benign slow-growing tumor that arises from the Schwann cells covering the vestibulocochlear nerve. The vestibulocochlear nerve is the eighth cranial nerve (CNVIII) and is a sensory nerve that facilitates hearing and balance. Symptoms caused by a vestibular schwannoma correlate with the size and growth of the tumor. The most common early symptom is hearing loss. Small tumors can cause hearing loss, tinnitus, and dizziness. As the tumor expands into the cerebellopontine angle—the anatomic space between the cerebellum and the pons—hearing loss may worsen, facial weakness can occur, and balance problems may worsen. Large tumors can compress the brainstem, with severe compression causing all of the above symptoms as well as headaches and visual problems [6]. While small tumors or those causing few symptoms can be observed, surgical removal is the most common treatment for large tumors. The goal of surgery is to (1) maintain facial nerve function, (2) preserve socially useful hearing in the affected ear, and (3) remove as much tumor as possible. Total tumor removal carries a higher risk of hearing loss and facial nerve damage so surgeons often opt for partial or near-total tumor removal in order to preserve neurological function [7].

There are three main approaches to remove a vestibular schwannoma based on tumor size, location, and hearing status [8]. With a suboccipital (retrosigmoid) approach, an incision is made behind the ear and through the occipital bone to expose the internal auditory canal and the tumor. With a translabyrinthine craniotomy, the approach is through the ear in the mastoid bone. The semicircular canals are removed to expose the tumor resulting in complete sensorineural hearing loss in the ipsilateral ear. A middle fossa approach is above the ear in the temporal bone, exposing the internal

auditory canal and the tumor. This approach can be used for small tumors and when hearing preservation is optimal.

During any of these approaches, the use of intraoperative monitoring can further assist the surgeon in locating and protecting cranial nerves. Surgeons often choose to utilize EMG for CNVII to protect from surgical manipulation damage to the facial nerve or if the facial nerve is being directly affected by the tumor. A very large tumor may require EMG for CNV as well. Once the tumor is removed, the integrity of the facial nerve can be tested by electrically stimulating at points proximal and distal to the site of tumor resection. A good prognosis for facial nerve function is if low-intensity proximal and distal muscle responses are the same [9]. Additional studies suggest a low threshold post-resection response of 0.05 mA or lower with response amplitudes >240 μV is indicative of preserved facial nerve function [10, 11].

CNVIII is monitored using BAEPs, not only watching the risk to the nerve associated with stretching or compression but also detecting changes in the function of the brainstem. With a translabyrinthine approach, hearing is sacrificed but monitoring BAEPs on the contralateral side can help protect brainstem integrity. According to Angelo and Møller, recording of the BAEP makes it possible to detect insults to the brainstem before changes in cardiovascular function become apparent [12].

Chiari Malformation

A Chiari malformation (CM) is a condition in which the cerebellum herniates through the lower part of the skull and down into the spinal canal. The herniated tissue compresses the brainstem and blocks the normal flow of cerebrospinal fluid (CSF) causing a build-up of CSF in the spinal cord. This can result in a fluid-filled cavity in the surrounding white matter called a syrinx, and the condition is known as syringomyelia (Fig. 14.4). Chiari malformations are found in both children and adults and are often difficult to diagnose. Symptoms can be variable from one patient to another and are not always related to the size of the herniation. Treatment options depend on the type of malformation and the severity of the symptoms, which can range from headaches, neck pain, and vertigo to numbness in extremities, vision problems, hearing loss, fatigue, and depression.

If symptoms worsen or medications are no longer effective, a posterior fossa decompression may be necessary to create room for the cerebellum and the brainstem.

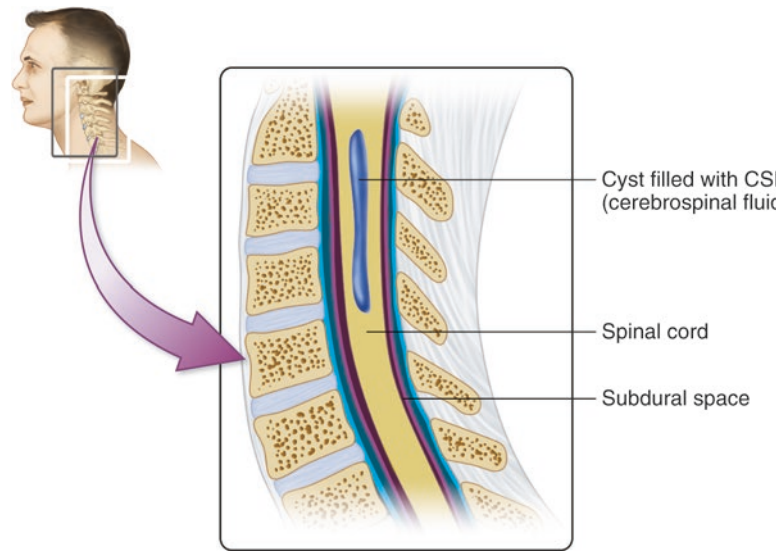

Fig. 14.4 Syrinx

There are four grades of Chiari malformations (CM Type I–CM Type IV) [13]. In Type I, the lower part of the cerebellum, called the cerebellar tonsils, extends into the foramen magnum. Type I is the most common form of CM and may not always cause symptoms. It is usually discovered during later childhood or early adulthood. Type II is where both the cerebellum and brain stem tissue are extending into the foramen magnum. Patients often have symptoms that are more severe than Type I and appear during infancy or childhood. Also seen with Type II is a form of spina bifida called myelomeningocele, where the backbone and spinal canal have not closed properly [14]. CMIII and CMIV are the most severe and are discovered at birth or with intrauterine ultrasound. This section discusses only the pathology of Chiari malformation Type I.

Beyond the cerebellar tonsils being displaced, a high incidence of patients with CM Type I will develop syringomyelia, which can cause irreversible damage to the spinal cord [15]. In addition to symptoms resulting from the cerebellar herniation, a patient's myelopathic symptoms may be attributed to an expanding syrinx. Compression of the brainstem and cranial nerve nuclei can occur as well leading to issues with sleeping, breathing, facial pain and numbness, and hearing loss.

In order to stop the progression of the herniation or if symptoms are worsening, a posterior fossa decompression is performed to reduce pressure on the cerebellum and spinal cord and restore the normal flow of CSF. An incision is made down the back of the neck, exposing the bottom of the skull and the top of the spine. A suboccipital craniotomy removes a small section of the skull. A C1 laminectomy may also be required for full decompression. Bony decompression will relieve pressure on the herniated tissue, but to fully restore CSF flow, the dura may need to be opened and then replaced with a larger autologous or synthetic dural patch. Shunting of the syrinx may also be necessary to drain CSF and relieve compression of the spinal cord.

Multiple structures and neurological functions can be at risk during surgery for a Chiari malformation. IOM is typically chosen to protect the brainstem, cerebellum, and spinal cord. As with other posterior fossa surgeries, BAEPs are used to monitor the integrity of the brainstem and effects of retraction on the cerebellum. The ascending and descending pathways of the spinal cord and brainstem are also at risk. The use of somatosensory evoked potentials (SSEPs) and transcranial motor evoked potentials (TcMEPs) will provide monitoring of the dorsal column pathway and corticospinal tract, respectively, as they pass from the brainstem into the spinal cord.

Conclusion

It is an understatement to say that multiple vital structures are in close proximity to one another in the posterior fossa. The anatomy of this area is very complex, and these vital structures can be difficult to identify, especially if a tumor has altered the anatomy even further. Neurosurgical procedures of the posterior fossa can involve the cranial nerves, brainstem, cerebellum, and the spinal cord. The use of multimodality IOM—using EMG and evoked potentials (SSEPs, TcMEPs, and BAEPs)—assists the surgical team in identifying structures at risk, as well as verifying structural integrity at the close of the procedure.

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Intraoperative Monitoring for Carotid Endarterectomy

15

Scott Francis Davis and Jeremy Andrew Bamford

Introduction

Carotid endarterectomy (CEA) is the most frequently performed procedure for the prevention of stroke. Strict selection criteria are applied to determine surgical candidates for CEA as indicated for the treatment of moderate to severe carotid stenosis. Carotid endarterectomy is associated with procedural and periprocedural risks including stroke (embolic or hemodynamic), myocardial infarction, as well as cranial nerve palsy resulting from traction on the recurrent laryngeal nerve. Recent attention has turned to a less invasive surgical approach to treat carotid stenosis, carotid stenting. Stenting and endarterectomy have shown comparable efficacy, but more randomized studies are needed [1].

Carotid revascularization by endarterectomy involves clamping the common, external, and internal arteries so that the vessel can be incised and the plaque removed. The ability of the patient to tolerate the cross-clamp depends on the sufficiency of collateral flow through the circle of Willis. Prior to routine intraoperative monitoring of cerebral perfusion, the surgeon would place an intraluminal shunt in all patients for the purposes of maintaining blood flow around the clamp. Routine shunting has been largely abandoned in favor of selective shunting [2–5]. In selective shunting, the need for a shunt is determined by intraoperative electrophysiological monitoring data [6]. The incidence of procedural embolic stroke is possibly correlated with the use of intraluminal shunts [4, 7]. This could be explained by the increased chance of introducing particulate emboli when the shunt is inserted through a diseased arterial wall. However, the literature is not in agreement that selective shunting reduces intraoperative stroke complications over routine shunting and more randomized studies are called for [8]. The monitoring community, nevertheless, advocates selective shunting, because the need for a shunt can be determined with high sensitivity and specificity with the use of electrophysiological monitoring methods. In addition, continuous monitoring can detect ischemic changes during other critical phases of the procedure as well as monitor the function of an intraluminal shunt if placed. In order for selective shunting to be safely performed, a means for assessing collateral flow and monitoring ongoing cerebral perfusion must be utilized. Older methods of monitoring, such as measurement of carotid stump pressure and cerebral oximetry, have either been replaced or become adjunct to the

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

J. A. Bamford
Department of Anesthesiology, Louisiana State, University Health Sciences Center, New Orleans, LA, USA

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modalities of EEG and median nerve SSEP [9–12]. Transcranial Doppler studies may be added to monitor for particulate emboli associated with clamp release and reperfusion as well as intraoperative ischemia [13–15].

It is essential that the neuromonitorist understand the critical phases of the endarterectomy procedure and the risks associated with each phase. Determining the likely cause of intraoperative changes, such as whether a stroke is embolic or hemodynamic in nature, is critical to providing relevant information that may be used by the surgeon or anesthesiologist to formulate an intraoperative treatment plan and prevent a negative outcome.

Intraoperative monitoring of CEA should include multiple modalities including EEG and median nerve SSEP [16, 17]. Continuous monitoring is advised even once a shunt has been placed as the integrity of the shunt may fail and go undetected by the surgeon. An appreciation for the endarterectomy procedure is necessary to insure appropriate attention is paid to all times of increased risk of neurological injury as complications are not restricted to clamping [18]. Both technical and professional monitoring personnel must be well trained and familiar with alarm criteria as well as recording parameters for monitored modalities.

Carotid Stenosis

Stroke is one of the leading causes of death and disability in the United States, and carotid stenosis is one of the leading causes of stroke [19]. Stenosis can occur in any artery in the body and is a result of the accumulation of atherosclerotic plaque buildup on the arterial wall. The most common sites for stenosis are arterial bifurcations. At an arterial bifurcation, blood flow is turbulent and there is more opportunity for plaque accumulation. A good analogy for this process is a fork in a river. The fork is the point along the course of a river where you are most likely to encounter "white water" and find debris along the riverbanks. Carotid stenosis occurs most often at the bifurcation of the common carotid into the internal and external carotid arteries (Fig. 15.1).

Carotid endarterectomy is the surgical option for the treatment of carotid stenosis. Stenosis that occurs much higher near the intracranial segment of the internal carotid artery cannot be treated

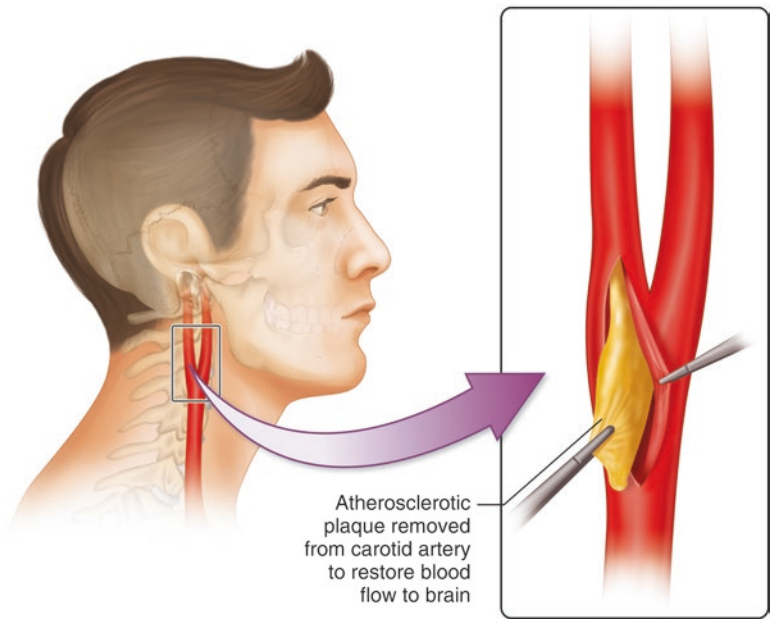

Fig. 15.1 Illustration showing the carotid bifurcation and the removal of plaque at this site by endarterectomy

with endarterectomy, and carotid artery stenting must be considered [20].

Selection Criteria for CEA

Carotid endarterectomy carries with it the risk of stroke and death along with the risks associated with general anesthesia [21–23]. For this reason, the risk to benefit ratio should favor surgical intervention. Recent studies have led to strict selection criteria for patients undergoing CEA. Current selection criteria support CEA for symptomatic patients with severe (>70%) and moderate (50–69%) stenosis as well as asymptomatic patients with severe stenosis. Other factors taken into consideration include comorbidities that may increase the perioperative complication rate, history of ipsilateral stroke, and life expectancy [24–26].

Preoperative Testing

EEG and SSEP testing may be performed on a patient prior to the day of surgery. This is not required for accurate intraoperative neurophysiological monitoring of the patient but may be useful in determining whether any abnormalities or asymmetries may be expected in the operating room. The existence of preoperative asymmetries should heighten the awareness of the monitorist of an increased potential for change during cross-clamping especially if there are any residual neurological symptoms following a prior stroke [27]. It is important to utilize the results of preoperative testing for the purposes of planning while remembering that the patient's intraoperative (post-induction) baselines will be the only data that matter during the monitoring procedure.

Anesthesia for Monitoring of CEA

The anesthetic regimen for intraoperative neurophysiological monitoring of any surgical case is determined based on the modalities to be monitored. For monitoring of most endarterectomies, the anesthetic requirements for SSEP and EEG recordings are to be considered [28]. Anesthesia and intraoperative monitoring is reviewed elsewhere in this volume. When monitoring of the recurrent laryngeal nerve is included in the monitoring protocol, the avoidance of muscle relaxants would also be essential. In the absence of preoperative EEG and SSEP testing, a preinduction baseline can illuminate any asymmetries due to a prior ischemic event. No further importance should be given to preinduction data, as the post-induction baseline will be the data against which changes are judged.

The pattern of EEG will change as the patient proceeds through the various states of anesthesia [28, 29]. Rapid induction, especially with barbiturates, will result in an alpha/beta pattern dominant in the frontal channels. As the stage of anesthesia moves toward the surgical plane, this activity will generalize and then begin to slow. Increases in volatile anesthetics beyond 1 MAC may result in a burst suppression pattern in the EEG, which is not conducive to monitoring EEG. If the EEG is in burst suppression, it is important for the monitoring team to inform the surgeon that EEG monitoring is currently unreliable and then begin to work with the anesthesia team to adjust the regimen to one more permissive of EEG monitoring. Anesthetic protocols may involve the use of minimal inhalants with the addition of a propofol infusion. In many instances, it is preferable to have the volatile agent higher as long as it does not exceed 1 MAC and the propofol infusion rate lower. It would be better to avoid a propofol infusion altogether since propofol can lead to a concentration-dependent burst suppression of the EEG. While it is optimal to have data from multiple modalities available when making interpretations, it is worth noting that SSEPs can still be reliably monitored even when the EEG is in burst suppression [30, 31]. Good communication with the anesthesia team prior to the case will help insure that such interruptions in monitoring are kept to a minimum.

Changes in the anesthetic load will also affect the reliability of SSEP data. Symmetric changes in the cortical potential (N20) can be suggestive

of anesthetic change, but the possibility of a surgical or peri-surgical cause cannot be ruled out. An asymmetric reduction in the amplitude or latency increase of the N20, however, is suggestive of a clinically significant change over an anesthetic-induced change. It is important that the anesthesia team be aware that changes in anesthetic load (e.g., delivering a bolus) are undesirable, especially near the time of or during an important surgical step.

Monitoring the patient's physiological status is an important job of the anesthesia team. The neurophysiological monitoring clinician can aid the anesthesia team by correlating change in physiological status with cerebral perfusion. One of the most important functions of the anesthesia team during the procedure is the regulation of the mean arterial pressure (MAP). Unlike most spine procedures, the CEA requires that the patients' MAP be carefully regulated at different points during the procedure [32]. For example, the MAP is increased during clamp to facilitate collateral circulation but reduced just before unclamping to avoid reperfusion injury. In addition, many patients undergoing CEA have a history of cardiovascular disease and hypertension, which may impede the ability of the arterial system to autoregulate. The consequence of this is that the patient may not tolerate the mean arterial pressure that they are being maintained at by the anesthesia team. Changes in neurophysiological data not correlating with a surgical step may be a result of changes in MAP. This becomes even more critical during both clamping and reperfusion (clamp release) when MAP must be carefully regulated.

Procedure Details and Critical Phases for Monitoring

While continuous neurophysiological monitoring is essential, there are critical phases of the procedure that warrant specific consideration due to the increased risk (Fig. 15.2). Thompson and Talkington [32] provide a good review of the procedural details of carotid endarterectomy. For the purposes of intraoperative monitoring of the procedure, it is important that the monitorist establishes quality baseline data for all modalities

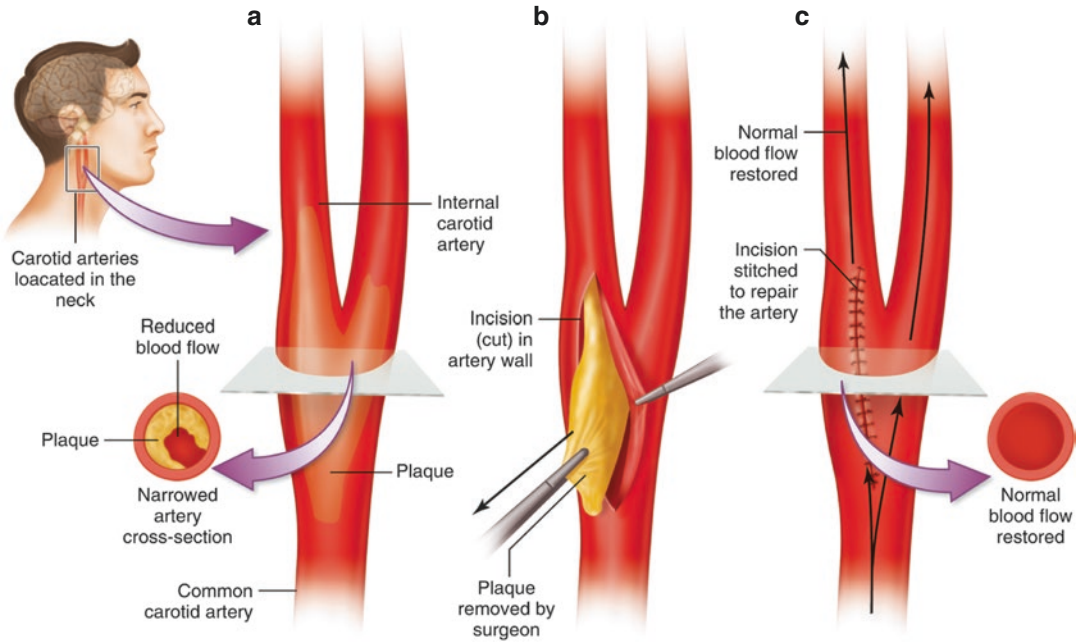

Fig. 15.2 The surgical steps of carotid endarterectomy

monitored after induction but well before cross-clamp. Premedicated baselines should be considered when possible solely for the purposes of revealing any preoperative asymmetries. At least a post-induction 10-min pre-clamp baseline should then be established for the purposes of comparing testing results throughout the procedure [33].

The first critical event is the administration of heparin. Heparin, an anticoagulant, is given prior to carotid cross-clamp for the purpose of preventing thrombus formation that may lead to embolic stroke on reperfusion. By the same mechanism, heparin may re-aggravate any bleeds that may have occurred from aneurysms or other disorders. It takes 4–5 min on average for heparin to raise the active clotting time sufficiently to proceed with carotid cross-clamping.

The next critical event, carotid artery cross-clamping, is likely the reason the surgeon has ordered monitoring to begin with. As you recall, the carotid arteries feed the ipsilateral anterior circulation of the brain. In most healthy patients, the contralateral circulation compensates for the loss of blood flow from one carotid artery. This compensation occurs by virtue of collateral circulation through the circle of Willis. A majority of people have an incomplete circle of Willis, of which there are many variants (Fig. 15.3) [34]. Although incomplete, the circle of Willis is still adequate to provide sufficient collateral circulation in most people. There are, however, certain anatomic variants or pathological conditions (including prior stroke) that result in the inability of the contralateral circulation to compensate for a unilateral carotid occlusion such as occurs during carotid clamping [35]. Changes in electrophysiological data that correlate with carotid cross-clamping should be taken as an alarm that collateral circulation is inadequate to perfuse the brain. A further discussion of alarm criteria will be presented below. In order to facilitate endarterectomy, the common, external, and internal carotid arteries must all be clamped. When collateral circulation is judged inadequate by changes in electrophysiological data, the surgeon will place an intraluminal shunt whose purpose is to reroute blood around the clamp maintaining

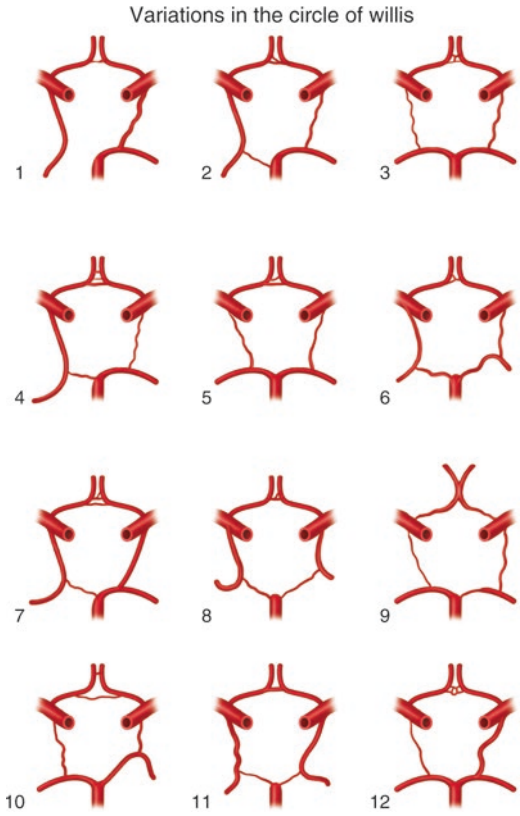

Fig. 15.3 Illustration of 12 variations seen in the circle of Willis

flow to the brain. Due to the increased risk of embolic stroke with shunt placement, the current standard is to shunt selectively as determined by changes in the monitoring data [4, 6, 7]. The anesthesia team must carefully manage the patient's blood pressure during cross-clamp. In order to support collateral circulation, the blood pressure is elevated above normal pre-clamp levels. Sufficient blood pressure can be titrated by carefully observing electrophysiological data from SSEPs and the EEG. Insufficient perfusion will result in a loss of amplitude from recorded signals providing a functional assay that can be used to determine the best blood pressure for the patient.

While carotid cross-clamping is largely considered the most critical phase of the endarterectomy procedure by many, reperfusion is the phase during which the patient is most at risk of suffering a stroke. When the carotid cross-clamp is

released, particulate emboli are released into the circulation. Most of these emboli are too small to cause a problem, but occasionally larger emboli may become lodged in a smaller vessel creating an obstruction [36]. If the obstruction occurs in a cerebral vessel, the resulting ischemia will likely be detectable as a change in SSEP or EEG data prompting intervention. A subcortical obstruction, however, will likely go undetected by routine monitoring modalities. Figure 15.4 shows an example of a clamp-related change in SSEP and EEG data and recovery of these data following insertion of an intraluminal shunt.

Reperfusion injury may occur secondary to a condition known as cerebral hyperemia [37]. Hyperemia can happen in any organ and is the result of too much blood flow. Hyperemia commonly known as reactive hyperemia may occur after a period of ischemia, which, in the case of CEA, may occur during carotid cross-clamp [38]. Hyperemia may develop in the postoperative period and occasionally develops intraoperatively sometime after clamp release. The increase in blood flow seen in hyperemia may cause an increase in intracranial pressure (ICP) that can compress the brain resulting in injury. Transcranial Doppler is the most useful modality in detecting postoperative hyperemia.

EEG Monitoring

Continuous EEG monitoring is used intraoperatively to assess the adequacy of cerebral perfusion and help determine the need for a shunt during carotid endarterectomy [39]. Intraoperative EEG monitoring for carotid endarterectomy does not necessitate recording as many channels as diagnostic EEG. A minimum of eight channels is required for intraoperative monitoring, while the use of more channels is encouraged [40]. The generator of the EEG signal is the cerebral cortex, and as such only cortical perfusion may be monitored with this modality. Subcortical events, such as embolic stroke, are unlikely to be detected with EEG.

EEG monitoring has the advantage of allowing direct monitoring of cerebral function as opposed to modalities such as stump pressure or TCD that only provide an indirect measure of cerebral function. Only SSEPs have demonstrated equal sensitivity to EEG [16]. The addition of median nerve SSEPs, thus, provides a necessary redundancy to EEG monitoring. Hemodynamic changes that do not affect the EEG can usually be assumed to be clinically insignificant, unless an effect is seen in the SSEP recording. EEG monitoring has largely replaced cerebral oximetry for carotid monitoring; however, oximetry may still be used as an adjunct in some centers. Cerebral oximetry measures regional oxygen saturation from the frontal lobes and primarily samples venous blood [9, 11, 12]. The effect of changes in oximetry on cerebral function must be inferred in contrast to the direct information provided by EEG. The following sections provide technical information on setting up and running the intraoperative EEG for monitoring a carotid endarterectomy. The reader is encouraged to become familiar with professional practice guidelines and position statements [41, 42].

Electrode Placement

Stainless steel subdermal needle electrodes are most commonly used for intraoperative EEG with some centers still opting for cup electrodes. The use of needles facilitates a safe and efficient recording setup without the use of adhesives. Electrodes should have an impedance of less than 5 kΩ. A minimum of eight channels of EEG should be recorded for monitoring of carotid endarterectomy. There are several acceptable montages for EEG monitoring of CEA. Table 15.1 shows one of the more commonly used montages often referred to as the modified double banana. A referential montage refers all active leads to a common cephalic reference (usually Cz). In a bipolar montage, active leads are referenced to each other giving the added advantage of increased specificity or ability to more easily locate the area of change. Since efficiency is required in the operative setting, many monitorists make use of their SSEP scalp leads in their EEG montage. The most important considerations are that the choice of recording sites contains areas from frontal to occipital and that leads are placed symmetrically on the left and right side.

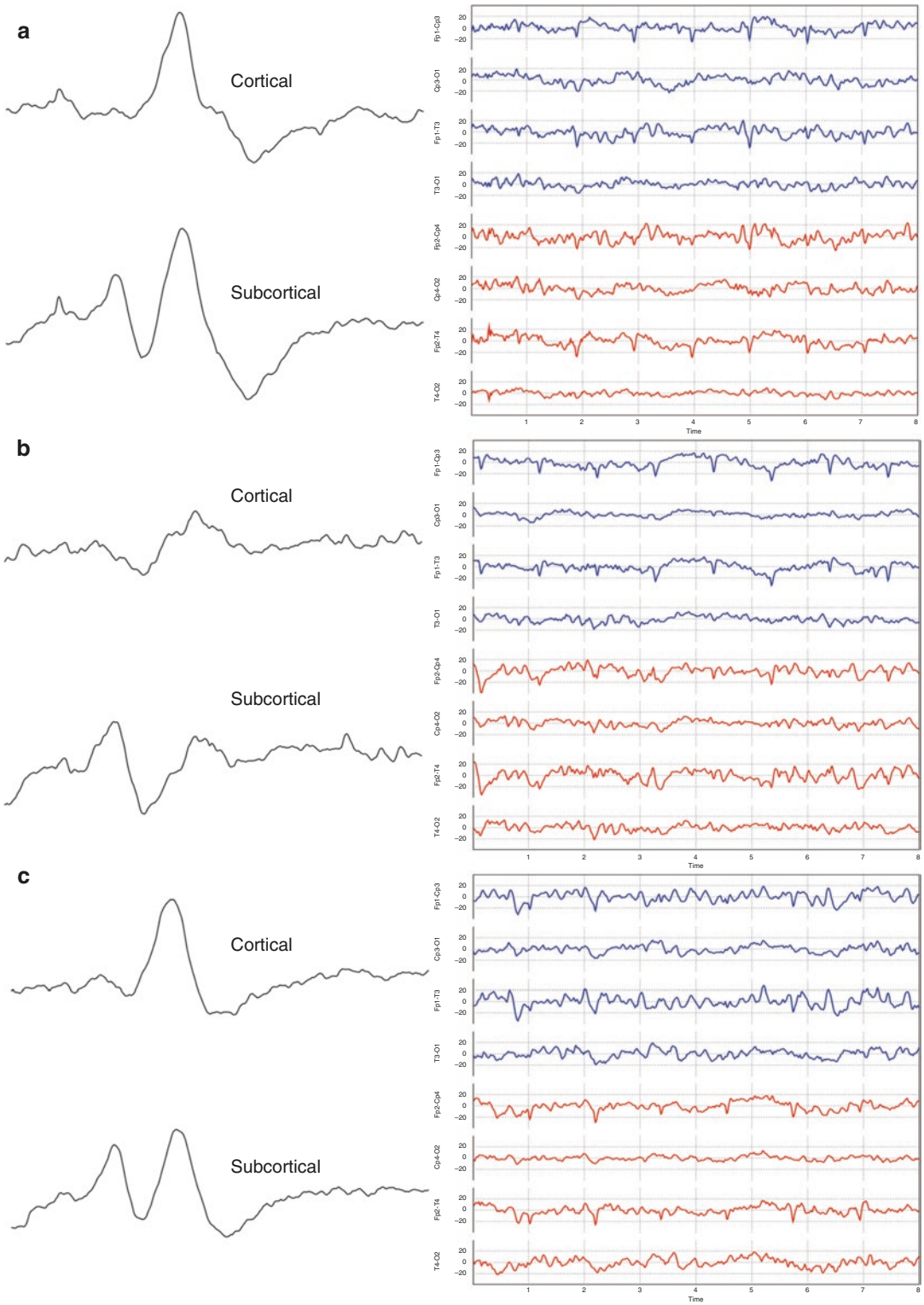

Fig. 15.4 Clamp-related SSEP and EEG change (**a**) SSEP and EEG baseline data established prior to carotid cross-clamp. (**b**) Data taken immediately after carotid cross-clamp showing amplitude reductions in the left cortical SSEP and left EEG. Note no change in the subcortical SSEP data. The generator of this potential is supplied by the posterior cerebral circulation. (**c**) Data taken after shunt placement showing recovery of all amplitudes

Table 15.1 Modified double banana electrode placement

Left	Right
Fp1-Cp3	Fp2-Cp4
Cp3-O1	Cp4-O2
Fp1-T3	Fp2-T4
T3-O1	T4-O2

Recording Parameters

Intraoperative EEG recording should have a bandpass of 0.5–70 Hz. Higher frequency signals such as the gamma band are not seen intraoperatively since they are associated with cognitive function. A notch filter may be used, but only when all attempts at eliminating the source of 60 cycle noise have failed.

Sweep speed (time base) may be set according to the preference of the monitorist with equivalent paper speeds of 10–30 mm/s being the most common. Shorter time bases make it easier to detect changes in the fast beta activity. This activity is generally the first to disappear in an ischemic event.

Sensitivity should be set such that the waveforms are not clipped (sensitivity too high) or appear to be flat (sensitivity too low). Intraoperative EEG is generally of lower amplitude than diagnostic EEG and thus is best viewed between 30 and 50 μV/cm.

Analyzed EEG

The advent of digital EEG has led to the ability to instantly analyze the raw EEG waveform and represent the composite waveform as a spectrum of its component frequencies. This type of analysis is termed spectral analysis and is accomplished with a fast Fourier transform (FFT) algorithm. To perform spectral analysis, the raw EEG waveform is sampled at a desired rate that is set by the user. The composite waveform (sample) is deconstructed into its component frequencies using FFT. The results are displayed graphically showing the power of each frequency band in the composite signal.

Spectral analysis can be useful during a carotid endarterectomy to confirm suspected changes in frequency detected by visual interpretation of raw EEG. It is important to note that the analyzed EEG is not a substitute for the raw EEG and that the raw data should be used as the primary source for interpretation [43].

Alarm Criteria

Alarm criteria for EEG are not widely agreed upon. Correlating different degrees of EEG changes with the postoperative outcome and assigning a weight to the type of change (amplitude reduction, general slowing, reduced fast activity, etc.) is problematic. One commonly used set of criteria include a 50% or greater reduction in amplitude associated with slowing. When less significant changes are judged to be clinically significant, the specificity of the EEG decreases. In spite of the possibility of decreased specificity, it is reasonable to take as clinically significant any change that correlates with a critical surgical event (such as clamping). Future studies may better define safe windows for change. Most clamp-related changes in the EEG recording occur within the first 20 s in most patients with the remainder of patients showing changes within the first minute. Occasionally clamp-related changes may be seen as late as 4 min post-clamp. There are data correlating changes in analyzed EEG with the postoperative outcome; however, one should be cautioned about using analyzed EEG to predict outcome in most practical settings.

SSEP Monitoring

The use of median nerve SSEPs has become a standard adjunct to continuous EEG monitoring during carotid endarterectomy. While MN-SSEPs provide specific protection to the somatosensory cortex, they have demonstrated remarkable sensitivity to cerebral ischemia resulting from carotid cross-clamp. It has been argued that SSEPs are even more sensitive to ischemia than EEG. The ease of SSEP interpretation compared with that of EEG may result in fewer missed occurrences when monitored by personnel less comfortable

with EEG interpretation. Such events cannot be attributed to a failure of EEG monitoring, but rather interpretive error.

Stimulation Parameters

Adhesive surface electrodes are predominantly used for stimulation of the median nerve. Placement of the stimulating electrodes is between the tendons of the palmaris longus and flexor carpi radialis muscle (approximately 2 cm proximal to the wrist crease). Care should be taken to make sure the cathode (stimulating pole) is proximal to the anode in order to prevent the phenomenon of anodal blocking. In rare instances, subdermal needle electrodes may be used when there is a patient history of peripheral neuropathy, body habitus, or edema.

A square-wave monophasic pulse with a pulse width of 200–300 μs is used as the stimulus. The pulse should be delivered at a frequency of approximately 3–5 pulses per second, taking care that the exact frequency is not divisible evenly by 60 so as not to average in-line noise. The intensity of stimulation should be supramaximal. To titrate the supramaximal intensity, the current is increased stepwise until no additional increases in the amplitude of the response are measured and then 10% is added to this intensity.

Recording Parameters

Median nerve SSEPs are recorded using a peripheral, subcortical, and cortical channel. The peripheral potential is recorded with the active electrode in the ipsilateral Erb's point and referenced to the contralateral Erb's point. The resulting signal is a peak of negative polarity and a latency near 9 ms. The generator is the brachial plexus. The N9 is most useful in determining the adequacy of stimulation as well as for monitoring the brachial plexus for positional issues. The subcortical (often called cervical) potential is recorded with an electrode usually placed around the C5 vertebrae. Alternate active electrode sites include over the mastoid bone, the earlobe, and the chin. The negative peak recorded at 13 ms and the corresponding trough at 14 ms are generated by the dorsal column nuclei and caudal medial lemniscus respectively. These potentials, similar to the N9, are not affected by anesthesia and are located caudal to the tissue at risk. The cortical potential is of greatest interest during a CEA. It is most commonly recorded with the active electrode at Cpc referenced to Fpz. Some monitorists prefer a non-cephalic reference such as the contralateral Erb's point if the fast frontal EEG commonly recorded from Fpz becomes problematic. The N18 is another peak of interest. Generated by the thalamus, this peak is recorded with the active electrode at Cpi referenced to the contralateral Erb's point. The thalamic potential is supplied by the posterior circulation. Monitoring this thalamic potential may be useful in detecting ischemia resulting from the phenomenon of posterior steal where too much blood is provided to the anterior circulation from the circle of Willis at the expense of posterior perfusion.

Alarm Criteria

Alarm criteria for SSEP monitoring are well agreed upon in general. For spinal cord monitoring, the widely accepted alarm criteria are a 50% reduction in amplitude and/or 10% increase in latency. Lam et al. [16] found that a reduction of 50% or greater in amplitude proved as sensitive as EEG monitoring for monitoring carotid endarterectomy. Similar to EEG changes, a minor or moderate change in SSEPs may or may not indicate an impending neurological deficit. It is clear that if minor SSEP changes are taken as an alarm, the overall specificity of SSEP monitoring will decrease significantly (more false positives). Until more research is done to define the significance level for SSEP monitoring for carotid surgery, many monitorists are more conservative with their approach to alarm criteria and report any change that correlates with a surgical event such as clamping or unclamping as significant.

Recent work by Reddy et al. [44] found that intraoperative SSEP changes correlated with an increased risk of postoperative stroke over

30 days after surgery. The postoperative stroke risk increases in a stepwise manner with the severity of the SSEP change.

Conclusion

Carotid endarterectomy is becoming one of the most commonly monitored surgical procedures. There are many opportunities for ischemic injury during the procedure, and the surgical and anesthesia teams must walk a fine line when regulating mean arterial pressure throughout the various phases of this surgery. Prior to the advent of patient monitoring, surgeons would place an intraluminal shunt in every patient. As it became evident that the use of a shunt increases the risk of an embolic stroke, surgeons began to look for ways to select patients for shunting based on the adequacy of collateral flow. Initial techniques used for this purpose were limited to measuring carotid stump pressure during clamping and possibly continuous monitoring of cerebral oximetry. Neither of these modalities provides both a continuous and direct measure of cortical function during surgery. Later on, intraoperative EEG became standard protocol for monitoring CEA. The addition of neurophysiological monitoring to the procedure provides assurance to the surgeon that the brain is being adequately perfused during the entire procedure. Although the sensitivity and specificity of EEG monitoring is quite good, many intraoperative monitorists lacked formal training in EEG making them uncomfortable or unqualified to interpret real-time EEG data for the purposes of assessing the adequacy of collateral flow. The addition of median nerve SSEPs to the monitoring protocol provided a familiar redundancy that could be used as an adjunct to EEG monitoring. With equal (if not greater) sensitivity and specificity to EEG, SSEPs have become a mainstay for intraoperative monitoring of carotid endarterectomy. Many centers now include transcranial Doppler monitoring to measure mean flow velocity in the middle cerebral artery and to detect emboli upon clamp release. The use of TCD for measurement of flow velocity does not provide the type of direct information on cortical function that EEG and SSEPs provide. In addition, the detection of emboli has not correlated well with clinical outcome.

Review Questions

1. Discuss three differences between routine and selective shunting. What role does IOM play?
2. What is the best course of action when noting a minor change in monitoring data that correlates with cross-clamping?
3. What is posterior steal and how can it be monitored?

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Monitoring ENT Procedures

16

Denise A. Birkholz and Scott Francis Davis

Introduction

Intraoperative neurophysiological monitoring (IOM) is used during surgeries of the head and neck, procedures to remove tumors of the thyroid, parathyroid, and parotid glands that put cranial nerves at risk, specifically the recurrent laryngeal nerve (RLN) (branch of CNX) and the facial nerve [1]. Monitoring and testing of the cranial nerves at risk accomplishes three goals: (1) to identify the nerve within the surgical field for the purposes of aiding the surgeon in avoiding damage to the nerve during the procedure, (2) to monitor the nerve during the course of the procedure in order to provide real-time feedback to the surgeon about the activity of the nerve, and (3) to provide the surgeon with a prognostic indicator of postoperative nerve function by assessing the stimulation threshold of the nerve at the end of the procedure [2]. These three goals of IOM for ENT procedures contribute to the overall mission of IOM to reduce the incidence of iatrogenic neurological injury. This chapter discusses practical applications of intraoperative monitoring for thyroidectomy, parathyroidectomy, and parotidectomy.

D. A. Birkholz
Neuromonitoring Associates, LLC, Las Vegas, NV, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

The Thyroid and Parathyroid Glands

The thyroid gland is one of the largest endocrine glands and is located in the anterior compartment of the neck, inferior to the thyroid cartilage. The thyroid is a butterfly-shaped gland consisting of a right and left lobe connected by an isthmus (Fig. 16.1). Anteriorly, it is covered by the infrahyoid (strap) muscles, and posteriorly, the gland is attached to the cricoid cartilage (just inferior to the thyroid cartilage) and tracheal cartilage. This is why the gland actually moves during swallowing.

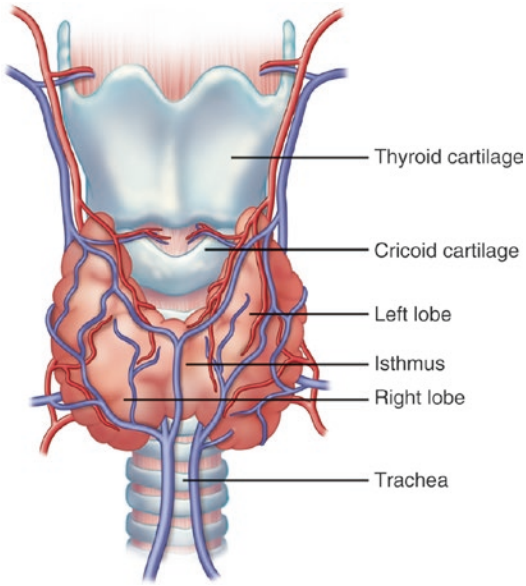

Fig. 16.1 The thyroid gland and surrounding structures

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The thyroid secretes hormones that help regulate the body's metabolism and affect the function of many other systems in the body. Located on the posterior surface of the thyroid are the parathyroid glands. There are typically four parathyroid glands, each about the size of a grain of rice, that are positioned in the upper and lower corners of the lobes on each side of the thyroid. The major function of the parathyroid glands is to secrete parathyroid hormone which maintains serum calcium homeostasis. During thyroidectomy, if parathyroidectomy is not indicated, the parathyroid glands are often saved and explanted into surrounding tissue where they will continue to function.

Thyroidectomy

Removal of the thyroid gland is indicated for a variety of conditions including tumor, goiter, or hyperthyroidism among others. Depending on the pathology, one (hemithyroidectomy) or both (total thyroidectomy) lobes may be removed. To access the thyroid and/or parathyroid glands, a horizontal incision is made across the front of the neck followed by a longitudinal incision through the strap muscles. Division of the local vasculature follows division of the musculature so that the lobes of the thyroid can be mobilized. RLN identification is the first goal of IOM for thyroidectomy and is essential for the purposes of avoiding the nerve during the procedure. Identification of the RLN is only assured when electrical stimulation results in a recorded compound muscle action potential (CMAP) from the vocalis muscle on the EMG recording.

The Recurrent Laryngeal Nerve

The RLN is a branch of the vagus nerve (CNX) that supplies motor function and sensation to the larynx. It innervates all of the intrinsic muscles of the larynx except the cricothyroid muscle, which is innervated by the superior laryngeal nerve (SLN). The RLN branches from the vagus nerve at the level of the subclavian artery on the right and the aortic arch on the left. After looping under the respective artery, the RLN ascends along the tracheoesophageal groove. The paired nerves are named "recurrent" because after branching, they turn back or run in a direction opposite to the vagus nerve. A minority of patients have a nonrecurrent laryngeal nerve branching off the vagus nerve at the level of the cricoid. During surgery, the RLN can be injured in a number of ways: complete or partial transection, traction, compression, misplaced ligature, thermal injury, or ischemia [3]. If the RLN is injured, it can result in temporary or permanent nerve paralysis. If the damage is unilateral, the patient may wake up with hoarseness. If there is bilateral nerve palsy, the airway may be compromised, resulting in dyspnea and in severe cases the need for a tracheostomy. The RLN also provides sensory innervation to the glottis, and a deficit may result in problems swallowing. Rates of injury range from 1% to 8%, with significantly increased risk to the RLN when surgery is for re-exploration, thyroid carcinoma, and total thyroidectomy [3–5]. In addition to thyroid and parathyroid procedures, the RLN is often monitored during ACDF, aortic arch procedures, carotid endarterectomy, and posterior fossa surgeries in order to avoid potential injury due to traction or nerve entrapment between the cuff of the ET tube and the retractor blades [6–8]. The SLN can also be injured during surgery [9, 10]. To monitor the SLN, the surgeon must place electrodes/needles in the cricothyroid muscle [9, 10]. Damage to the SLN results in a monotone voice or inability to change pitch.

RLN Monitoring

Spontaneous and triggered EMG recorded from the vocalis muscle is used to monitor the RLN. During thyroid and parathyroid procedures, it is imperative that two channels are available to monitor both the left and right vocal cords. Endotracheal (ET) tubes with left and right electrodes integrated directly into the tube are commercially available. Alternatively, commercially available adhesive paired electrodes

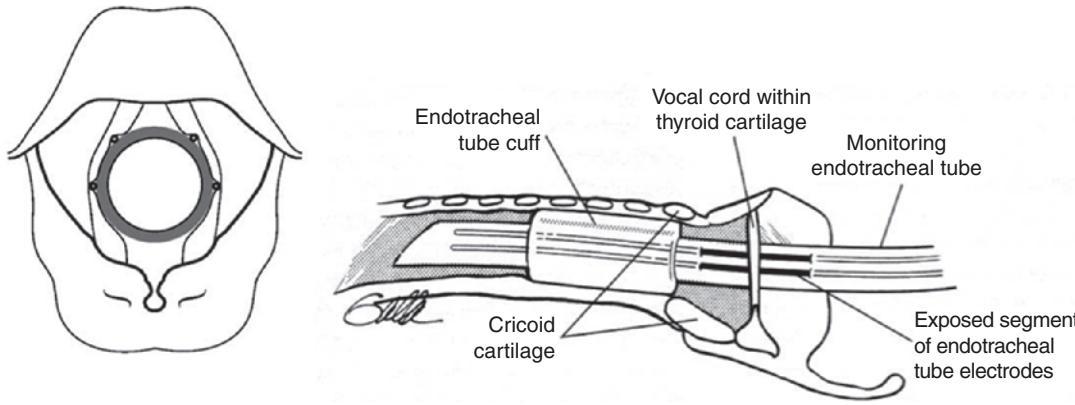

Fig. 16.2 Proper placement of endotracheal tube electrodes

can be attached to standard ET tubes. Proper placement of the electrodes of the endotracheal tube is of critical importance [2, 11, 12] (Fig. 16.2). Early communication with the anesthesia team will greatly aid in confirming proper electrode placement. The neuromonitorist should request a short-acting paralytic for intubation such as succinylcholine and avoidance of lidocaine, as these drugs will impair early recording ability for the purposes of confirming correct electrode placement [2]. Even though the anesthesiologist will be placing the endotracheal tube with electrodes, the monitorist should be knowledgeable about proper placement. It should be emphasized to the anesthesiologist that visual confirmation of the electrodes in contact with the vocal cords is essential. The electrode recording surface is often a blue strip or ring depending on the electrodes used. Common misplacements include electrodes that are too superficial, too deep, or a rotated tube [2].

Unlike EMG from spinal nerve myotomes, baseline EMG recorded from the vocal cords should exhibit baseline activity. Baseline EMG amplitudes of 25–50 μV are most commonly observed with proper electrode placement because the presence of baseline activity is because the vocal cords are contracted at rest and relaxed when speaking. Failure to record baseline activity may be due to a number of factors including misplaced tube, the use of lidocaine, or residual neuromuscular blockade. Asymmetric baseline activity may indicate that the ET tube and electrodes are rotated and not in contact with one side of the vocal cords. Inadequate baseline recordings will prevent proper monitoring during the case and could result in false-negative results. It is important to correct electrode placement if necessary. This is accomplished by asking the anesthesiologist to move the endotracheal tube while the monitorist views the live EMG recording. As the electrodes move into proper position, the amplitude of recorded activity on the screen will increase. The tube depth showing maximal EMG activity should be marked where the tube meets the teeth, and the tube should then be secured. It is not unusual for baseline activity to decrease in amplitude during the procedure as a result of changes in electrode impedance resulting from secretions.

Identification of the RLN is one of the first steps in the thyroidectomy procedure. One technique, called sweeping, is used to aid the surgeon in initial dissection. Monopolar stimulation is used for the sweeping technique. The surgeon is given a handheld monopolar probe and the monitorist will stimulate continuously (at approximately 2 mA) while the surgeon sweeps the field in search of the nerve. The presence of a CMAP response indicates that the nerve is in proximity. There are technical considerations that the monitorist should be aware of during sweeping. The presence of blood or irrigation in the surgical field may shunt current away from the nerve and prevent a response from being seen despite proximity of the nerve to the stimulator [2]. It is therefore important that the surgical field remain dry when stimulating.

The stimulation parameters for sweeping are different than for direct nerve stimulation. The first difference is the use of a monopolar stimulator versus a bipolar stimulator used for direct nerve stimulation. Monopolar stimulation induces a larger current field and is said to be more sensitive than bipolar stimulation. Bipolar stimulation (having the cathode and anode in close proximity) has a smaller current field and while less sensitive is more specific. The stimulation intensity used for sweeping is higher than for direct nerve stimulation. Continuous stimulation up to 3 mA (pulse width not to exceed 50–100 μs) is performed until a response is seen. Once a response is recorded at supramaximal intensity, the intensity is reduced and the threshold for response determined. If there is no current shunting, the stimulation threshold can be used as an indicator of the distance to the nerve. The response should likewise increase in amplitude as the stimulator approaches the nerve.

When the surgeon is ready to confirm the identity of the RLN, direct nerve stimulation is the optimum method [13, 14]. Direct nerve stimulation uses a bipolar stimulator to find the threshold of activation by increasing the intensity of stimulation in 0.1 mA increments starting from 0 mA. The pulse width should not exceed 50–100 μs, and the stimulation intensity should remain <2 mA. A CMAP recorded from the vocal cords with a latency of approximately 2 ms is confirmation of the identity of the RLN (Fig. 16.3). The stimulation threshold at this point can be used as a comparison to values at closing, possibly offering prognostic information to the surgeon on the function of the RLN.

It is possible for the monitorist to not record a response to stimulation even when the surgeon expresses confidence that she/he is stimulating the RLN. There can be several reasons for this apparent discrepancy. The monitorist should immediately work to confirm that there are no technical issues preventing stimulation and recording. As mentioned earlier, the tube must be properly positioned to insure accurate recording, and this can be confirmed by recording of baseline spontaneous activity on both RLN channels. The presence of a stimulation artifact as well as measurement of current return will serve as confirmation of adequate stimulation. Once technical issues are ruled out, attention should turn to nature of the structure being stimulated. If the surgeon reports seeing a response visually within the field, then she/he is most likely stimulating a motor nerve or a muscle directly. Often a visual response without EMG confirmation is due to stimulation of the SLN. If this is suspected, a pair of sterile needle electrodes can be handed off to the surgeon and placed in the cricothyroid muscle and an EMG response recorded. If there is no visual evidence of stimulation, then the surgeon may not be stimulating neural tissue or is possibly stimulating a sensory nerve, which will not produce an EMG response. The monitorist must develop confidence when communicating these possibilities to the surgeon as well as helping the surgeon work through which scenario is most likely.

After identification of the RLN, continuous spontaneous EMG monitoring of the vocal cords is used in order to avoid injury to the nerve.

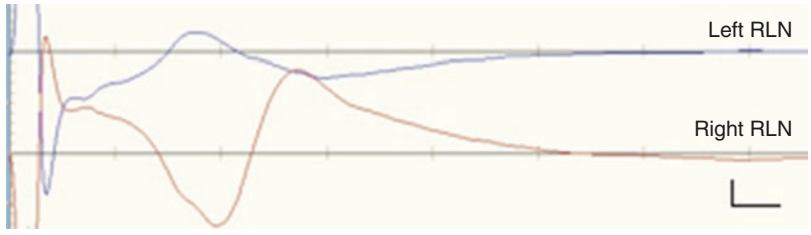

Fig. 16.3 Compound muscle action potential in response to stimulation of the RLN. CMAP recorded from the vocal cords bilaterally in response to stimulation of the right RLN. The stimulation intensity was supramaximal at 2.0 mA, causing the large resultant CMAP to be recorded in both channels. Scale bars indicate 1 ms and 100 μV

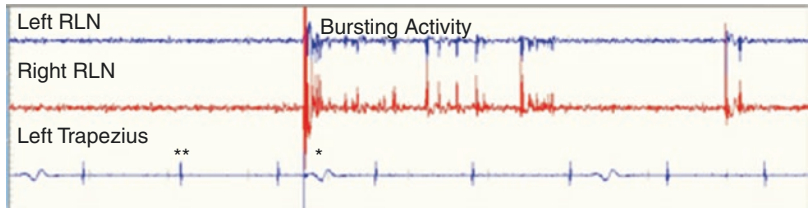

Fig. 16.4 Spontaneous EMG. Baseline EMG activity recorded from the vocal cords bilaterally and the trapezius (as a control). Note the tonic background activity of the RLN channels. Present in this record is bursting activity on the RLN channels. EKG (*asterisk*) and stimulation artifact (*double asterisk*) are seen in the trapezius recording

Spontaneous EMG is best viewed at a time scale of 200 μs/division and display sensitivity of 200 μV/division (Fig. 16.4). Occasional spiking or bursting patterns indicate non-injurious proximity to the nerve while more clinically significant patterns of activity include training and neurotonic discharge. These latter two patterns should be immediately reported to the surgeon. The use of audio EMG is useful in guiding the surgeon during the procedure. The surgeon may appreciate hearing spiking or bursting patterns as he navigates the surgical field. Spontaneous EMG is most useful in detecting impending nerve injury from stretch (retraction) or compression. Complete nerve transection may result in a quick burst of activity followed by electromyographic silence. However, ischemic injury may go completely undetected by EMG monitoring.

Direct stimulation of the RLN at the conclusion of the procedure is recommended to document the function of the nerve. A similar method, such as thresholding used when identifying the nerve, can be used to test the functional integrity of the RLN at closing. Comparable thresholds can be taken as evidence of no new nerve damage during surgery [2].

In addition to intraoperative stimulation and monitoring of RLN function with spontaneous EMG, pre- and postoperative assessment of vocal cord mobility is useful for determining both preexisting pathology and postoperative outcome [2, 15]. The discovery of preoperative hemiparesis is important information that the surgeon and monitorist should consider before proceeding with the procedure. Careful intraoperative monitoring to avoid a bilateral injury is essential.

Parotidectomy

The parotid glands are the largest of the salivary glands, located on either side of the face just inferior and anterior to the ear (Fig. 16.5). Innervation of the parotid glands is by the glossopharyngeal nerve; however, the facial nerve travels directly through the parotid gland on its way to innervate the muscles of facial expression.

The facial nerve emerges from the brainstem between the pons and the medulla. The main function of the facial nerve is motor control of the muscles of facial expression. Extracranially, the facial nerve passes through the parotid gland where it divides into five major branches. This is why it can be said that parotid surgery *is* facial nerve surgery. The parotid glands are a common site of tumor growth and as such may need to be surgically removed. The surgical plane artificially divides the parotid gland into a superficial and deep lobe, with the facial nerve as the dividing line. A superficial parotidectomy will take out the portion of the gland superficial to the nerve plane. A deep lobe, or total, parotidectomy removes both superficial and deep lobes relative to the plane of the facial nerve.

During parotid surgery, facial nerve monitoring can assist the surgeon with functional preservation of the nerve [16]. Spontaneous and triggered EMG of the facial nerve can help to locate and identify the branches of the nerve, warn the surgeon of unexpected stimulation, reduce injury due to retraction and cautery, and evaluate nerve function at the conclusion of the surgery [15]. The five facial nerve branches that pass through the parotid gland are the temporal, zygomatic, buccal, marginal mandibular, and

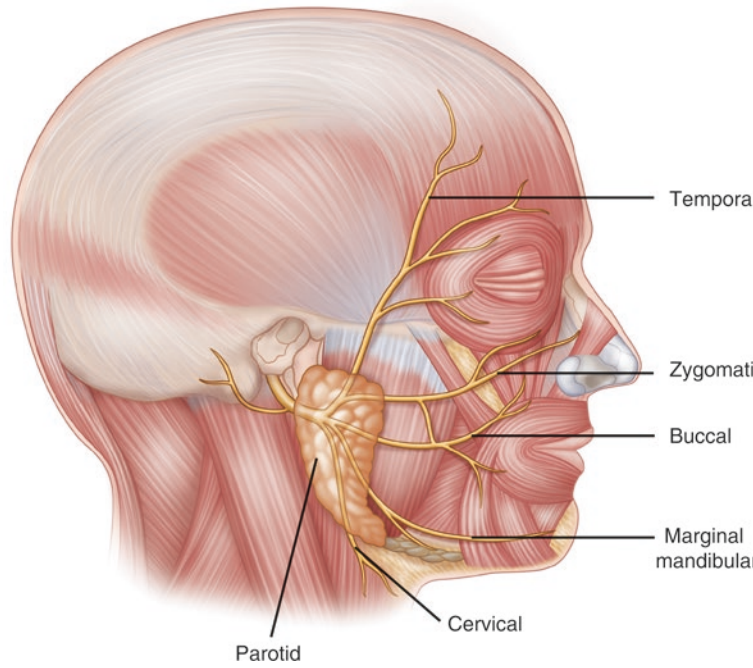

Fig. 16.5 Parotid gland and facial nerve

Table 16.1 Branches of the facial nerve and corresponding muscles for EMG

Branch	Muscles
Temporal	Frontalis
	Orbicularis oculi
Zygomatic	Orbicularis oculi
	Nasalis
	Zygomaticus major/minor
Buccal	Buccinator
	Orbicularis oris
Marginal mandibular	Depressor anguli oris
	Depressor labii inferioris
	Mentalis muscles
Cervical	Platysma

cervical. For a parotidectomy, needle electrodes are typically placed in muscles corresponding to at least four out of the five branches (the cervical branch is often not monitored). Muscles commonly used are listed in Table 16.1. Recordings made from the frontalis or orbicularis oculi may be slightly noisier than other channels due to contamination by frontal EEG signals. Stimulation of the facial nerve during surgery assists the surgeon in identifying the facial nerve and distinguishing neural from nonneural tissue. Like RLN monitoring, direct nerve stimulation is the only way to reliably identify the nerve [17]. Typical parameters used are a stimulation intensity of 0.1–2.0 mA with a duration of 50–100 μs [17]. The latency of the facial nerve response when stimulated at the brainstem is approximately 7 ms, but a response when stimulated at the parotid will be shorter, so time base should be adjusted accordingly. The stimulation threshold for the facial nerve should be recorded and compared with stimulation of the nerve following parotidectomy. At closing, functional integrity of the facial nerve can be assessed by stimulating each branch of the facial nerve. Closing stimulation thresholds of <0.5 mA are prognostic for normal postoperative function of the facial nerve [15, 17].

Conclusion

Identification by direct stimulation and continuous monitoring during head and neck procedures helps to reduce injury to cranial nerves. Intraoperative RLN and facial nerve monitoring can provide valuable real-time feedback regarding the location and function of the nerves, thereby decreasing the risk of permanent postoperative damage.

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Peripheral Nerve Monitoring

17

Amit Prabhakar, Kenneth Mancuso, Jonathan Lissauer, Alan David Kaye, and Scott Francis Davis

Introduction

The peripheral nervous system is comprised of a complex and vast network of nerves that work synergistically to achieve unique functions in the human body. Neuronal diversity lends nerves in this system to be vulnerable to a variety of injury types that have different management strategies. Peripheral nerve monitoring has been proven to be a useful asset for intraoperative management of nerve lesions. Physical examination alone of nerve lesions has been shown to be an unreliable and often misleading method to assess nerve integrity and regeneration. Intraoperative peripheral nerve assessment provides clinicians with unique, real-time information that is otherwise unavailable via preoperative nerve examination. This additional information can help to guide clinical decision-making and subsequently improve patient outcomes. This chapter will provide a brief overview of the physiology and anatomy of the peripheral nervous system, review nerve injury classifications, and detail the equipment and techniques utilized for effective intraoperative peripheral nerve assessment.

Overview of the Peripheral Nervous System

Before understanding the pathophysiology of specific lesions in the peripheral nervous system (PNS), it is imperative to have basic knowledge of both the anatomy and physiology of the PNS. The PNS serves many purposes in the human body including regulating motor, sensory, proprioceptive, and pain functions. The majority of peripheral nerves are myelinated; however, there is a subset of nerves that are unmyelinated. While myelin in the central nervous system is made from oligodendrocytes, myelin found in the peripheral nervous system is synthesized from Schwann cells [1]. The transition zone between the peripheral nervous system and central ner-

A. Prabhakar
Emory University School of Medicine, Department of Anesthesiology, Division of Critical Care, Atlanta, GA, USA

K. Mancuso
University Medical Center New Orleans, Department of Anesthesiology, New Orleans, LA, USA

J. Lissauer
Department of Anesthesiology, School of Medicine, Louisiana State University Health Sciences Center, New Orleans, LA, USA

A. D. Kaye
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

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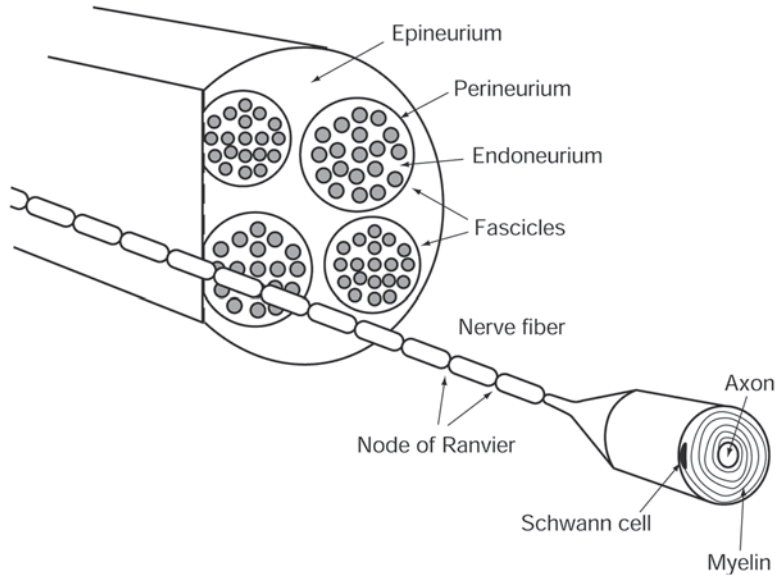

Fig. 17.1 Anatomical organization of a peripheral nerve. (Reproduced with permission from Sunderland [10])

vous system is called the Obersteiner–Redlich zone and is an area most vulnerable to injury [1]. Peripheral nerves contain many axons. Individual axons are separated from each other by a thin connective tissue sheath called the endoneurium. Groups of endoneurium-lined axons form fascicles that are surrounded by a connective tissue layer called perineurium. Groups of fascicles subsequently form nerve trunks, which are covered by the outermost layer called epineurium [2]. Figure 17.1 illustrates the organization of a peripheral nerve. The endoneurium, or central portion of the nerve, is composed of finer collagen fibrils when compared to the peripheral portions of the nerve. This in turn results in the central portion of nerves being more sensitive and fragile to traction [1].

Nerve fibers in the peripheral nervous system consist of the myelinated Aα, Aβ, and Aδ fibers and the unmyelinated C fibers (Table 17.1). These nerves are further classified based on axonal diameter, which also dictates nerve conduction velocity [1]. Motor nerves are made of Aα fibers, have the biggest diameter, and have the fastest conduction velocity at about 100 m/s [1]. Motor neuron cell bodies are located in lamina IX of the ventral horn of the spinal cord [3]. Sensory nerve fibers consist of the myelinated Aβ and Aδ and unmyelinated C fibers. These nerve fibers have cell bodies located in the dorsal root ganglia of the spinal cord [4]. Aβ fibers are mostly responsible for low-threshold cutaneous receptors and have an average conduction velocity of 50 m/s [5]. Nerves that are responsible for pain transmission consist primarily of the unmyelinated C fibers. These have the slowest conduction velocity [5].

Table 17.1 Conduction velocity in nerve fibers of different types

Fiber type	Function	Average axon diameter (mm)	Average conduction velocity (m/s)
Aα	Motor nerves, primary	15	100 (70–120)
	Muscle-spindle afferents		
Aβ	Mechanoreceptor afferents	8	50 (30–70)
Aδ	Temperature and pain afferents	<3	15 (12–30)
C	Pain afferents	~1	1 (0.5–2)
	Sympathetic postganglionic fibers		

Peripheral Nerve Injuries

Peripheral nerve injuries can result from a variety of mechanisms. A recent retrospective review of 1019 operative brachial plexus lesions showed

that the majority of lesions resulted from stretch or contusion and were in continuity. A smaller proportion resulted from tumors, gunshot wounds, and transection due to sharp laceration [6]. The management of injuries from sharp laceration and blunt transection is relatively straightforward, consisting of primary repair within 72 h and 2–3 weeks, respectively [7, 8]. However, lesions found in continuity pose several confounding variables that require extensive preoperative evaluation and planning [6, 7, 9]. Intraoperative neurophysiological assessment of peripheral nerve lesions is useful in determining continuity and establishing a treatment plan.

Classifications of Injuries

Focal peripheral nerve injuries can be classified into three main categories based on the morphological and functional features of the lesions: neurapraxia, axonotmesis, and neurotmesis. Lesions can also be divided into five groups known as Sunderland grades (Fig. 17.2).

Neurapraxia is the mildest form of injury. It is defined as partial or complete conduction failure without any structural changes in the support structures of the nerve [10]. This type of injury can also be classified as Sunderland grade 1. Etiology of this type of lesion can be due to excessive stretch, heat, or compression. The affected nerve is able to regain full function within several hours to days [1].

Axonotmesis is defined as the interruption of nerve axons without damage to its supporting connective tissue or glial structures. This is a more significant injury and can also be identified as Sunderland grade 2 [11]. Injuries such as this can also result from excessive stretch, compression, or pinching [1]. Lesions that occur distally to the cell body result in Wallerian degeneration of axonal components distal to the lesion. Wallerian degeneration is defined as the degenerative changes that occur in a segment of a nerve

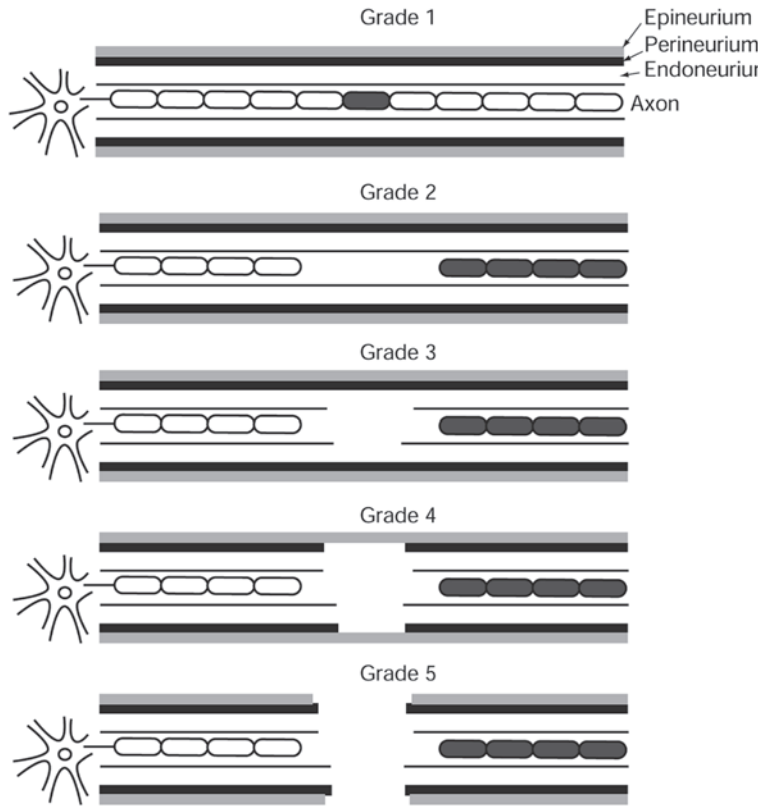

Fig. 17.2 Illustration representing Sunderland grading and showing the various degrees of conduction block and support structure changes inherent to each grade of injury. (Adapted with permission from Sunderland [2])

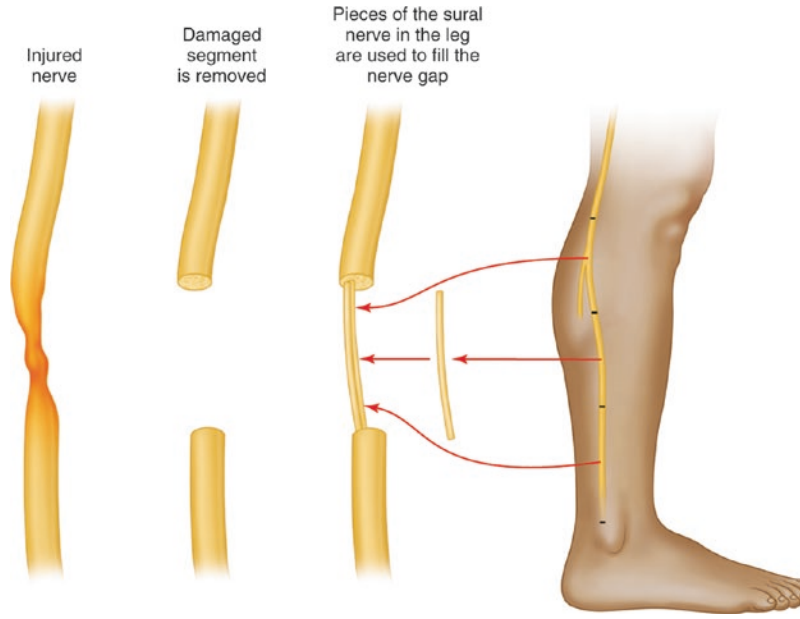

Fig. 17.3 An example of using the sural nerve to graft two segments of an injured peripheral nerve

fiber when continuity with its cell body is lost [1]. Wallerian degeneration begins immediately after the lesion has occurred and is usually complete within 48–72 h after the injury. It is important to note that the nerve may still be able to conduct impulses within the first 24–72 h after the injury [1, 11]. Intraoperative assessment in this immediate time frame, therefore, may be inaccurate.

Neurotmesis is defined as injury that involves both the axons and neural support structures such as Schwann cells and connective tissue layers. This is the most severe type of injury and can be further classified as Sunderland grades 3, 4, and 5 [10]. Sunderland grade 3 injury involves a mixture of support structure and axon damage. This degree of injury may be able to undergo partial regeneration without intervention and subsequently regain some level of function. Sunderland grade 4 injuries result in scar formation over the entire cross section of the nerve [12]. The differentiation between grade 3 and 4 lesions is essential because spontaneous regeneration may be blocked by scar tissue in grade 4 injuries. Thus for grade 4 lesions, surgical intervention is indicated to remove the offensive scar tissue and allow for optimal recovery [12]. Sunderland grade 5 injuries are the most severe form of injury and are described as total transection of a nerve. This degree of injury requires immediate surgical grafting in an attempt to restore any functionality. Nerve grafting involves surgical removal of the injured segment of the nerve and connecting the two functional ends with a graft taken from an autologous site. Usually the sural nerve is used to provide graft tissue (Fig. 17.3).

When considering the degree of neuronal injury, it is important to also understand the basic physiology of neuronal regeneration. Nerve regeneration is a complex process that is very different in humans compared to lower mammals, which have much greater regenerative capabilities [13–15]. As mentioned earlier, axonal components distal to the lesion undergo Wallerian degeneration, while the proximal part seals off at the point of division [12]. The proximal sealed portion will produce multiple sprouts of growing neurites within approximately 36 h of the injury. Regeneration occurs at a speed of approximately 1 mm/day [1]. This increase in growth can actually result in a greater concentration of axons distal to the lesion compared to proximal axon counts [12]. However, these growing axons have a much smaller diameter with distinct electrical properties [16–18]. They have much slower conduction velocities relative to normal nerves [12]. They also have significantly higher electrical thresholds relative to normal nerves. Effective regeneration is characterized by some fibers increasing in

diameter, while other finer fibers regress and die. Axons must reach a critical diameter in order to produce a useful motor unit. If the developing small-caliber fibers do not successfully increase in diameter, there is low probability that they will be able to form a meaningful connection with the corresponding muscle [12, 13, 15]. Thus the presence of numerous fine fibers may be indicative of either active early-stage regeneration or later-stage failed regeneration.

Preoperative Evaluation of a Peripheral Nerve Injury

Crum et al. detail four critical questions that should be addressed when evaluating all peripheral nerve injuries [19]. First, it is obviously vital to identify whether the problem is truly neurologic. Poor patient effort, pain, and the subjective nature of sensory examinations can decrease the accuracy of clinical evaluations. Next, it is important to localize the specific nerve that is affected. This is largely dependent on clinician knowledge of peripheral nerve anatomy and dermatome distribution [19]. The clinician must then try to identify where the lesion is located along the anatomical course of the nerve. Lastly, it must be determined whether the lesion is complete or not. As discussed previously, it is possible that lesions in continuity may be undergoing axonal regrowth that is not yet detectable via clinical examination alone. Prior to the advent of electrophysiological testing, surgeons had to rely on visual inspection to determine a course of treatment. Today, real-time electrophysiological recordings can provide an accurate diagnosis of the lesion, allowing the surgeon to formulate a well-informed treatment plan. Generally, lesions found to be in continuity are observed for subsequent regeneration, while lesions in which there is no continuity are grafted [6, 20].

Recording Nerve Action Potentials

Peripheral nerve lesions that result in axonal sprouting can form an accumulation of misdirected neurites known as a neuroma. Neuromas can be small or large and cause compression of the nerve resulting in even more injury. Frequently, functionally regenerating axons may pass through the neuroma on their way to reestablish connections with their targets. These are known as neuromas in continuity. Such neuromas in continuity may need to undergo neurolysis so the regenerative process may continue but do not require grafting. Neurolysis is the surgical freeing of the nerve from inflammatory adhesions and resulting traumatic neuroma. The concept of diagnosing a neuroma in continuity is a simple one; stimulate a peripheral nerve proximal to a lesion and use electrodes to monitor for a response distal to the lesion. Intraoperative monitoring can be accomplished using relatively simple and inexpensive equipment. The majority of commercially available EMG machines are able to effectively detect compound nerve action potentials (CNAPs). It has been estimated that a minimum of 4000 fibers are needed to produce a clear CNAP [21].

Since the size of most CNAPs is considerably larger than the typical evoked potentials recorded in operative monitoring, the process of signal averaging is not required [21]. The amount of stimulation required is dependent on the size of the nerve being studied. It is recommended that the stimulator be able to produce short pulses of 0.02–0.05 ms and intensities of up to 70 V [12]. The use of short-duration pulses helps to identify the type of fibers being stimulated. Fine fibers of regenerating axons and other small-diameter fibers are much less sensitive to short-duration impulses compared to healthy nerves [21]. Stimulation of nerves in short duration through electrodes in direct contact has been proven to be both safe and effective [21]. Longer-duration stimulation may result in electrical burns or other iatrogenic injury [21].

Electrodes used to stimulate and record CNAPs are also simple. They should fulfill certain characteristics, such as being durable, functional, and reliable, and have electrical properties conducive for use in electrical stimulation [12]. It is imperative that the electrodes never be made from silver due to the potential damage from deposited silver salts [12]. Stainless steel has proven to be a cheap, effective, and readily available option for elec-

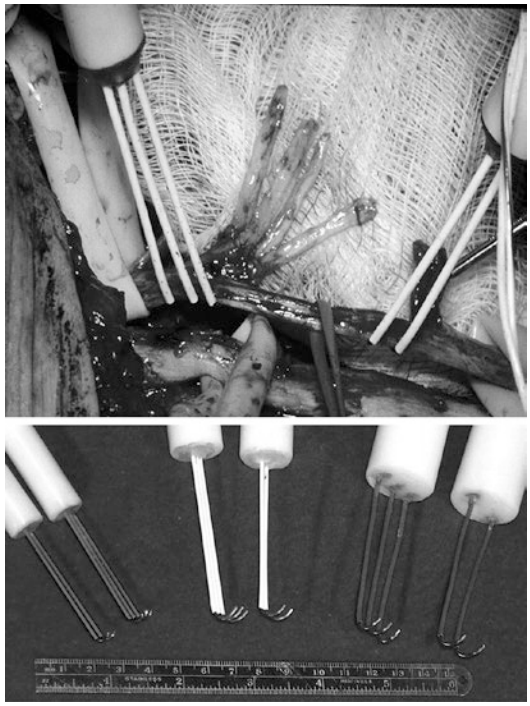

Fig. 17.4 *Top panel* shows tripolar stimulation and bipolar recording from a peripheral nerve intraoperatively. The electrodes span a few centimeters of the nerve. The *bottom panel* shows a selection of hook electrodes that may be used to stimulate and record from peripheral nerves. (Reproduced with permission from Happel [21], Fig. 35.1)

trode composition. Electrode size can be modified to better accommodate the size of the nerve being studied. Electrode tips can be bent into a "J" or hook shape in order to better grasp and isolate the desired nerve (Fig. 17.4). The stimulating electrode is usually tripolar, whereas the recording electrode is bipolar [21]. The tripolar configuration for stimulation helps to reduce stimulus artifact and limit spread of the stimulus. The amplitude of CNAPs recorded is dictated by the distance between recording electrodes [12]. The ideal distance between recording electrodes is anywhere from 3 to 7 mm, depending on the size of the nerve. If the electrodes are too close together, the recorded action potential can have falsely reduced amplitude. Reasoning behind this phenomenon is due to the characteristic saltatory conduction seen in myelinated nerves, being necessary for the recording electrodes to span at least one node of Ranvier [12, 16, 17].

Once the desired nerve is properly isolated, the electrodes are used to study CNAPs from both the proximal and distal segments of the nerve. If no CNAP can be recorded distal to the lesion in response to proximal stimulation, there is little chance that the nerve will be able to undergo primary regeneration. The ability to record a distal CNAP indicates that the lesion is in continuity. Precise determination of the location of the lesion may be accomplished using a technique known as "inching" or "walking" of the electrodes. This technique entails stimulating the nerve at short, incremental steps across a lesion and assessing the change in morphology and latency of the waveforms that are recorded distally [19, 22].

Technical Considerations

There are several technical aspects that need to be considered when evaluating a peripheral nerve injury. First, adequate exposure and isolation of the nerve being investigated is essential. This helps to ensure that the responses being recorded are truly representative of only the nerve being investigated [6]. Adequate isolation also ensures the electrodes are in good contact with the nerve [6]. The nerve should be free of both excess irrigation and blood to reduce the prevalence of stimulus artifact and shunting of current. The hook configuration of the electrodes may be used to slightly elevate the nerve out of any fluid. The exposed nerve will inevitably lose heat in the cold operating room environment. Healthy, cold nerves will have poor conduction velocity compared to normothermic healthy nerves [6]. Investigators recommend using warm saline prior to stimulation to prevent temperature distortion. If a tourniquet has been used, approximately 20 min should pass before nerve recordings take place. The use of excessive local anesthetic may also attenuate or block nerve conduction [6]. The temporal relationship between the intraoperative investigation and time of injury is just as important as the procedural aspects of investigation [23, 24]. As mentioned previously, no studies should be done on lesions in continuity within 72 h of the injury because that is still within the time frame of Wallerian degenera-

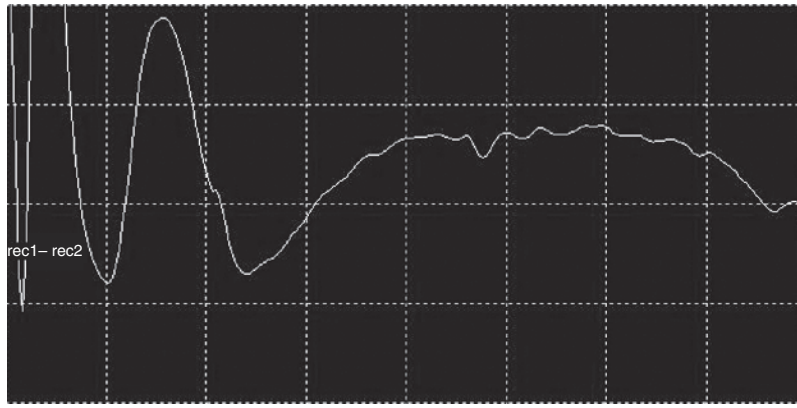

Fig. 17.5 A CNAP in response to stimulating and recording from a segment of peripheral nerve proximal to a tumor. The fact that the CNAP is normal in appearance is because it is recorded proximal to the tumor. The early latency suggests that there is a short distance between the stimulating and recording electrodes. (Reproduced with permission from Happel [21], Fig. 35.4)

tion. Lastly, care must be taken to ensure the distance between electrodes is adequate for correct interpretation of the signal. Recording a NAP over a known normal portion of nerve can be useful to serve as a control (Fig. 17.5). This can be beneficial if there is any question about the validity of an absent NAP over a lesion [19].

Anesthesia has little effect on either NAP or CNAP recordings. Neuromuscular blockade may be desirable to reduce excessive muscle artifact for NAP recordings [19]. Neuromuscular blockade should be avoided if muscle recordings will be performed with peripheral nerve stimulation. Inhalational anesthesia has no known effects on peripheral nerve monitoring.

Intraoperative Diagnosis and Treatment of Peripheral Nerve Injury

There are several characteristic findings of NAPs from injured nerves. First, an increase in latency can indicate impaired conduction velocity [25]. Latency is determined as the time between the onset of the stimulus and the earliest negative peak of the response [25]. A decrease in the amplitude of the negative peak in response to maximal stimulation can also be representative of fewer fibers being recruited (Fig. 17.6) [25].

Except in certain circumstances, lesions in continuity are generally treated by neurolysis, and then regeneration is allowed to proceed [19, 26]. Grafting of a nerve in continuity is only indicated in lesions with no documented CNAP and thus little or no chance for effective regeneration [9, 19]. Most nerves with a lesion in continuity are allowed to regenerate following neurolysis and do not require grafting. The treatment of a complete nerve transection is surgical intervention (grafting) within days to weeks of the initial insult [7, 8]. Figure 17.7 shows a flow chart that is useful in determining the course of treatment based on electrophysiological observations.

Specific Nerve Lesions

Carpal Tunnel Syndrome

Median neuropathy at the wrist is the most common entrapment neuropathy of the upper extremity [9]. Intraoperative nerve monitoring is seldom used in this scenario due to the effectiveness of preoperative evaluation and ease of the decompressive procedure. However, intraoperative studies have shown sites with the most abnormal NAPs correlated with the segment of most abnormal-appearing nerves [27]. The anatomical site noted to have the most abnormal conduction is within

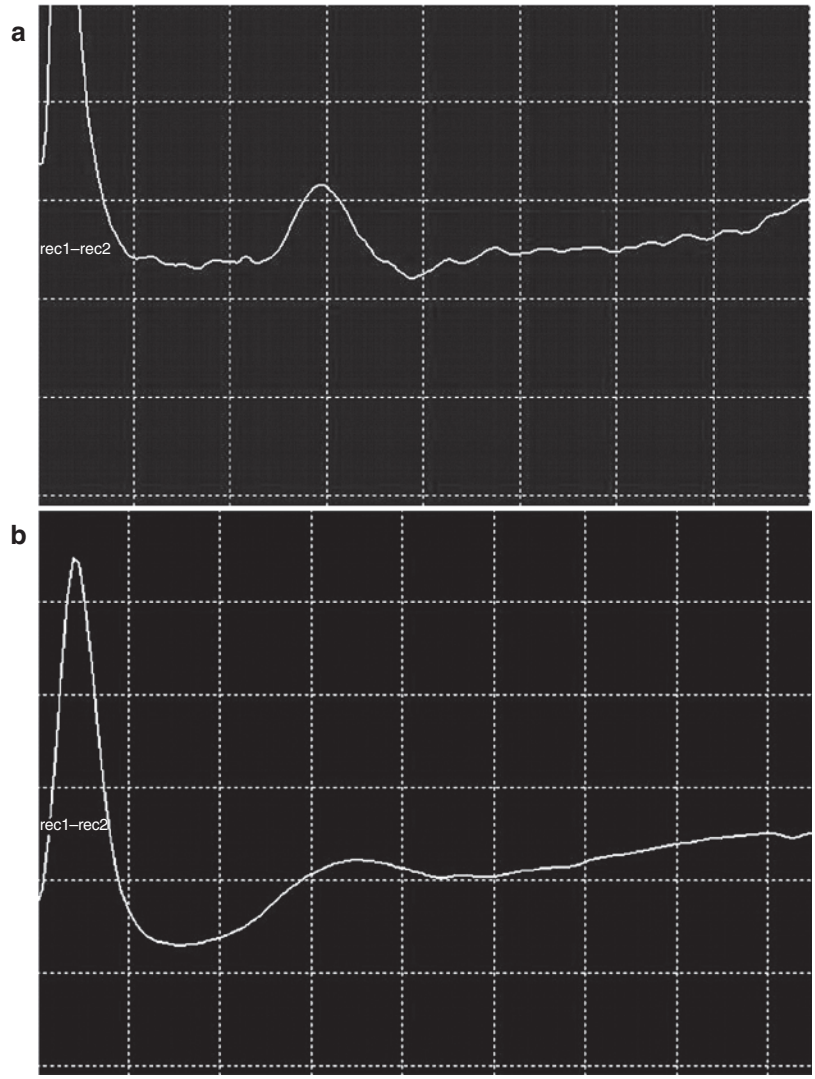

Fig. 17.6 (**a**) CNAP recorded from a nerve of the brachial plexus. Note the normal appearance of morphology and duration (scale: 200 μV/div, 1 ms/div). (**b**) Abnormal CNAP recorded from a nerve of the brachial plexus. Note the increased duration (area under the curve) and lower amplitude. Physiologically this suggests both changes in conduction velocities among the individual nerve fibers and recruitment of fewer fibers (scale: 200 μV/div, 1 ms/div). (Reproduced with permission from Happel [21], Fig. 35.2)

the first 10–20 mm distal to the proximal border of the flexor retinaculum. Conduction has been documented to either improve or stay the same immediately after median nerve decompression [28, 29].

Ulnar Neuropathy

Ulnar neuropathy at the elbow is the second most common entrapment neuropathy. The two most common anatomical sites for compression at the elbow are at either the cubital tunnel or retroepicondylar groove between the medial epicondyle and olecranon [9]. Preoperative nerve studies are able to confirm the presence of neuropathy but may not be able to localize the lesion between these two sites [30, 31]. This is important because the surgical approach for treatment is different for the two sites. Numerous studies have shown that the site most frequently implicated is at the level of the epicondyle [32]. This is a prime example where intraoperative monitoring can guide clinical management and improve patient outcomes.

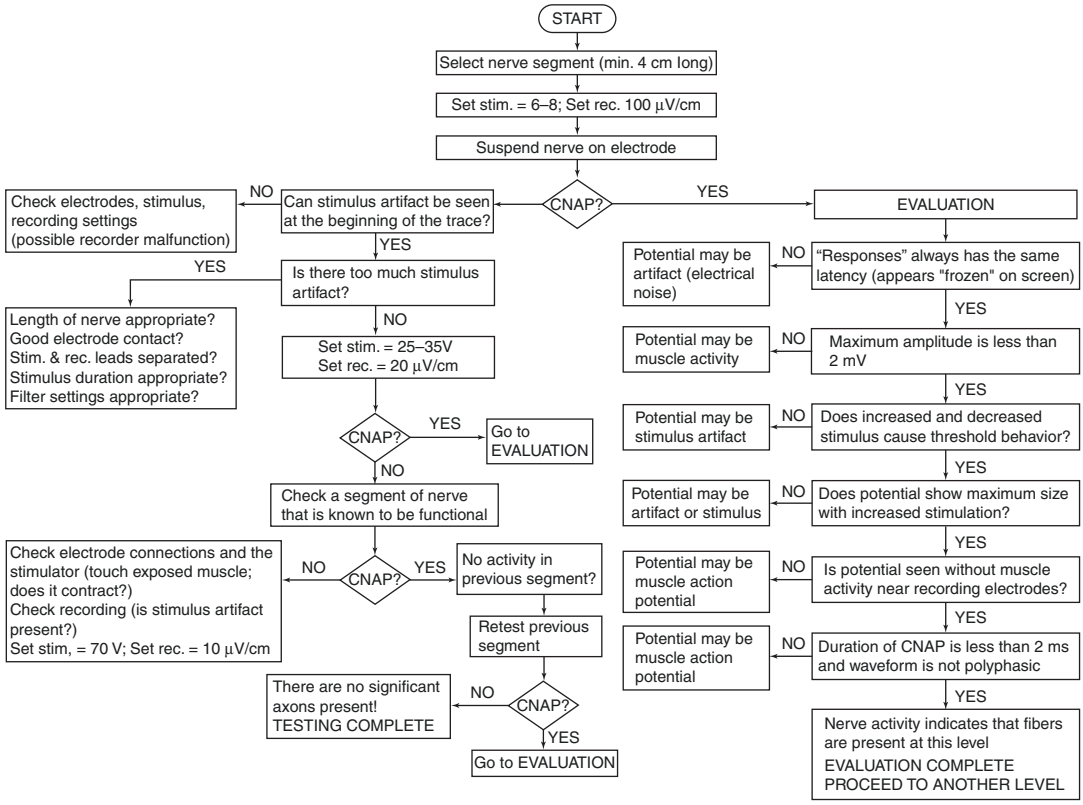

Fig. 17.7 Flow chart of clinical decision-making for intraoperative peripheral nerve diagnosis. (Reproduced with permission from Moller [34]. Fig. 15.3)

Common Peroneal Neuropathy

The common peroneal nerve is most commonly affected as it traverses the fibular head at the knee [9]. While identification of neuropathy can be identified preoperatively, intraoperative nerve studies can assist with localization and determination of nerve continuity [27]. A large series of surgically repaired peroneal neuropathies revealed that lesions with no NAP were much more likely to be due to trauma. These types of lesions were grafted. Lesions with recordable NAPs were most likely related to nontraumatic compression or entrapment. These lesions appropriately underwent neurolysis as opposed to grafting [33].

Conclusion

The vast majority of peripheral nerve injuries leave the nerve in some degree of continuity. Lesions in continuity may create a spectrum of damage within the nerve often precluding an accurate diagnosis with conventional preoperative EMG evaluation [21]. Intraoperative peripheral nerve monitoring synergistically combines several basic concepts that can help provide definitive and real-time information on the status of the fiber population within the nerve. Successful implementation is multifaceted and requires effective communication among the surgeon, neurophysiologist, and anesthesiologist. When used effectively, intraoperative peripheral

nerve monitoring has been proven to improve both treatment efficacy and patient clinical outcomes.

Review Questions

1. Discuss the five Sunderland grades of nerve injury.
2. What is the advantage of using tripolar hook electrodes for stimulation?
3. What can be inferred from an observed latency increase in NAPs?
4. Define and describe Wallerian degeneration.
5. What are the different nerve fiber types and how do their conduction velocities differ?

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18 Intraoperative Cortical Mapping: Basic Concepts, Indications, and Anesthesia Considerations

J. Arthur Saus, Charles Fox, Harish Siddaiah, Alan David Kaye, Scott Francis Davis, and Bharat Guthikonda

Introduction

The eloquent area of the brain is responsible for written and verbal communication. Functional neuroimaging indicates that interindividual variation exists with the anatomical location of the eloquent area of the brain. Some patients have shown significant contribution from areas located near, but outside of, the traditionally recognized eloquent area. Classically, these areas adjacent to or near the eloquent area were thought to have little impact on written or oral language skills, and many neurosurgeons, in the past, underestimated the impact of operating in these areas. Now, each patient is known to have a unique eloquent area. This necessitates intraoperative cortical mapping to more accurately identify functioning before removing brain tissues in patients undergoing epilepsy or brain tumor surgery in areas near this region of the brain. The goal of intraoperative cortical mapping is to maximize surgical resection in the eloquent area while minimizing the incidence of permanent disabilities. This chapter is intended to provide you with the concepts, indications, and anesthetic considerations important to intraoperative cortical mapping and to prepare you for further reading of more advanced texts and primary literature on this topic.

J. A. Saus · H. Siddaiah
Ochsner LSU Health, Department of Anesthesiology, Shreveport, LA, USA

C. Fox
Department of Anesthesiology, Louisiana State, University Health Sciences Center Shreveport, Shreveport, LA, USA

A. D. Kaye
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

S. F. Davis (✉)
Department of Anesthesiology, Louisiana State University School of Medicine, Tulane University School of Medicine, New Orleans, LA, USA

B. Guthikonda
LSU Health Sciences Center, Department of Neurosurgery, Shreveport, LA, USA

Concepts

Cortical Mapping: Historical Perspective

Dr. Robert Bartholow performed the first electrical stimulation of the cortex in 1874 on a patient named Mary Rafferty, a 30-year-old Irish woman who had been employed as a domestic servant. She presented with an infected scalp ulcer, which was diagnosed as cancerous. The physicians attempted to treat this surgically,

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leaving a 2-in.-diameter hole in her skull with exposed dura. Apparently after determining that nothing could be done to save her life, Dr. Bartholow proceeded to experiment on the exposed brain, reportedly with the patient's consent. By inserting needle electrodes into the exposed brain tissue and by applying small electrical currents to various areas, he noticed it caused movements in various parts of her body and did not cause pain, following the patient's initial complaints of neck pain with needle insertion. He also noted that application of larger currents resulted in seizure activity and what seems to be what we now recognize as a transient postictal state. Although it is reported that she returned to consciousness 20 min later, she complained of weakness and vertigo. As her condition worsened, her physicians did not do any further experiments, and she died a few days later. The conclusions from her autopsy were that although parts of her brain had been damaged from the electrodes, her death was due to her cancer and not to this experiment. Despite this "contribution to medical science," both British and American physicians severely criticized Dr. Bartholow and his "reckless use of living human beings," and the American Medical Association condemned his experiments, calling them "so in conflict with the spirit of our profession, and opposed to our feelings of humanity that we cannot allow them to pass unnoticed" [1].

Despite this criticism, and the fact that this hardly could be considered "cortical mapping" in any sense of our current use of the term, this provided to beginnings of understanding that electricity could be applied to different areas of the brain and that regional somatic activity would result. Research on electrical stimulation of human and animal brains continued, and in 1888 Dr. Nancrede mapped the motor cortex by the use of a battery-operated bipolar stimulator probe. Neurologists David Ferrier and Victor Horsley used cortical stimulation mapping techniques to research the function of the precentral gyrus and the postcentral gyrus in the late 1800s. In the early 1900s Charles Sherrington used monopolar stimulation to elicit responses and was able to determine that the precentral gyrus elicited a motor response and that the postcentral gyrus was a sensory cortex. Dr. Harvey Cushing confirmed these findings and was the individual primarily responsible for moving cortical mapping from an experiment into an accepted neurosurgical technique.

Prior to going into the techniques used in the process of cortical mapping and analysis of those determinations, we should first have some understanding of what a cortical map is. Most physicians and medical students have seen the diagram of the homunculus, as described in the 1930s by a Canadian neurosurgeon, Dr. Wilder Penfield, and probably remember an image of a human body displayed across a drawing of a human cortex, although in a somewhat disjointed manner, with a large elongated face in the lateral one-third, while the hand is in the next approximately one-third, and the rest of the body is in the next one-third, toward the most central part, then with the foot on the medial portion of each hemisphere (see Chap. 2). Most physicians will probably also remember that the sensory functions are shown as existing in the postcentral gyrus of the parietal lobe, just posterior to the central (or Rolandic) sulcus, while the motor function in the cortex is described as primarily in the precentral gyrus of the anterior lobe, just anterior to the central (Rolandic) sulcus (with a very similar homunculus image). In effect, this displays the most basic concept of a cortical map. Unfortunately, however, this homunculus diagram is a grossly inaccurate oversimplification. The anatomical view of the brain tissue does not always precisely correlate to localizing the functions as suggested by this diagram. Sensory and motor areas of the cortex can now be mapped much more precisely by electrical stimulation and recording of "evoked" responses.

Anatomic and Physiologic Basis

The cortex of the human brain is 2–4 mm thick and in most parts of the cerebrum contains six layers which can rather easily be demonstrated on microscopic examination. In general, sensory cortex is thinner and motor cortex is thicker [2]. Within the brain cortex, very small areas

(minicolumns) can be identified that perform a specific information processing function. Minicolumns grow from progenitor cells within the embryo and contain neurons within multiple layers (2–6) of the cortex [3]. A cortical minicolumn is a vertical column through the cortical layers of the brain, comprising approximately 80–120 neurons, except in the primate primary visual cortex where there are typically more than double this number. There are about 200,000,000 minicolumns in the human cortex. Many sources support the existence of minicolumns, especially Mountcastle [4] with strong evidence reviewed by Buxhoeveden and Casanova [5] who conclude "…the minicolumn must be considered a strong model for cortical organization" and that the minicolumn is "the most basic and consistent template by which the neocortex organizes its neurones, pathways, and intrinsic circuits." It appears that this minicolumn structure is the primary means of organization in the cerebral cortex not only of humans but of other animals as well.

From multiple examinations and calculations, various researchers have estimated the diameter of a human minicolumn is about 28–60 μm. These minicolumns also contain downward projecting axons that are approximately 10 μm in diameter, with periodicity and density similar to those within the cortex, but not necessarily coincident. The probable estimated size of a minicolumn can also be calculated by area considerations: if the surface area of a human cortex (both hemispheres) is 1.27×10^{11} μm^2 and if there are 2×10^8 minicolumns in the cortex, then the cortical surface area of each minicolumn is 635 μm^2, giving an average diameter of 28 μm (but even if the cortex area were doubled to the commonly quoted value of 2.5×10^{11} μm^2, this would rise to 40 μm). Johansson and Lansner do a similar calculation and arrive at an estimated minicolumn size of 36 μm.

There is also evidence from studies published in 2000 by two separate researchers, Buxhoeveden and Buldyrev, that spacing of 50–80 μm exists between adjacent columns. All cells in a single minicolumn have the same receptive field; adjacent minicolumns may have very different fields. Thus, a stimulus applied to a specific sensory nerve elicits a response within specific cortical minicolumns and does not necessarily elicit responses in immediately adjacent minicolumns in the cortex. This columnar arrangement forms the anatomic basis for the ability to perform cortical mapping. However, electrodes which are used for cortical mapping currently have a diameter of 2–3 mm, so we cannot electrically stimulate each discrete minicolumn but instead electrically stimulate a field containing hundreds of minicolumns with (hopefully) common functionality.

Maps of these cortical areas may be demonstrated in different ways such as texture maps, color maps, and contour maps. However, despite the existence of these maps, even for those attempting to localize the fields of "minicolumns," which subserve a particular function in a human brain, it can be challenging. The brain retains a great degree of plasticity, such that if one of these areas is damaged, much of the function designated to that specific area can be "taken up" or assumed by a nearby area. Thus, designated maps can change with experience.

As an example of this plasticity phenomenon, people who read Braille (which is done with an index finger) develop large areas responsive to stimulation from the index finger. A homunculus mapped on the motor cortex of such a person would have a relatively huge index finger. This phenomenon contributes to the lack of accuracy and specificity of a "brain map" that the standard homunculus diagram would otherwise suggest is present in the human brain.

The cytoarchitecture of the cerebral cortex enables the recording of local positive and negative potentials over the cortical surface corresponding to the projection of cortical axons. As discussed in Chap. 4, this phenomenon is known as a dipole. The projection of dipoles varies among locations of the cortex, but the projection of the dipole of neurons in the primary somatosensory cortex (postcentral gyrus) is in the anterior–posterior plane. Furthermore the zero-potential or mid-dipole point lies over the central sulcus. As such, recording the cortical peak of the median nerve SSEP from a row of electrodes placed directly on the cortical surface is used as a means of locating the central

sulcus and therefore both the primary motor and sensory cortical areas. The point at which a phase reversal (between positive and negative potentials) is seen can be reliably marked as the central sulcus. See Fig. 4.3 in Chap. 4 for an example. Once the relative location of the motor cortex is identified, it can be further mapped as described below.

Equipment and Technique

So how is cortical mapping accomplished? The mapping is done during a craniotomy by stimulating the sensory or motor cortex with a weak electric current, usually for a few seconds, once the dura mater has been peeled back. This electrical stimulation acts as a transient reversible virtual lesion, interrupting the normal electrical activity in that localized area of neural tissue. This "lesion" can either induce or prevent a specific motor or sensory response that can be tested and evaluated. For example, the stimulation may produce tingling in part of the body, or movement in part of the body, or it can interfere with a normally spoken word.

As mentioned earlier, the electrodes currently used are usually circular with diameters of 2–3 mm. They are usually made of stainless steel or a platinum/iridium alloy and imbedded in a Silastic material. Due to difficulty in re-sterilizing them, they are single-use devices.

Stimulation for mapping is commonly performed according to one of two techniques. Using continual electrical stimulation (Penfield's method), constant current is applied using a bipolar stimulating electrode at a frequency of 50–60 Hz. A biphasic square wave pulse with duration of 400–1000 μs is used in order to avoid charge buildup on the surface of the brain. *A monophasic square wave pulse is not safe to use for this type of high-frequency continuous stimulation*. A more modern stimulation technique used for mapping of the somatic motor areas is known as direct cortical electrical stimulation (DCES) or simply MEP mapping because of the similarity with transcranial motor evoked potential monitoring. DCES makes use of a pulse train as opposed to continuous stimulation. Monopolar anodal stimulation is used for DCES and due to the use of brief pulses; monophasic square waves are an acceptable stimulus. A train of 4–9 pulses with duration of 50–500 μs is usually effective. Electrodes may be placed individually or more usually in a row or in a grid array. The electrical current applied must be enough to stimulate the neurons for an adequate duration yet low enough to avoid damaging them. Whether using MEP mapping or Penfield's technique, the "dose" of the current is usually started low and then gradually increased in both intensity and duration until a response is elicited. So initial intensities of 1 mA are a commonly used starting point. The current is then gradually increased by 0.5–1 mA with successive tests until a desired response is noted. It is important to identify the stimulation intensity that is adequate to produce activation of the neural tissue. Afterdischarges are nerve impulses that occur after stimulation, and the presence of afterdischarges indicates that the maximum amount of current that can be safely applied to the cortical surface has been reached. Monitoring for the presence of afterdischarges using electrocorticography (ECoG) is necessary to avoid the complication of seizure during cortical stimulation and also provides a measure of the adequacy of stimulation (see Chap. 10).

In situations where surgery needs to be performed to remove cerebral tissue, such as for tumor resection, or when an incision must be made through this more superficial cerebral tissue to get access to a deeper structure, a specific determination of the areas of the patient's brain controlling a specific function becomes important. Likewise, it is also important to know where the "silent" areas are that surround these functions. The surgical goal may be to affect a particular cortical area or to specifically avoid affecting a few or many of these cortical areas.

Within this context, identification of "eloquent cortex" becomes quite important. Eloquent cortex is a term used by neurologists and neurosurgeons for areas of cortex that result in a loss of sensory processing or linguistic ability or some degree of loss of sensory or motor function if it is damaged or removed. These defined areas of cortex are crucial for certain particular functions, and some areas are indispensable for a particular cortical function [6]. The most commonly recognized

areas of eloquent cortex are in the left temporal and frontal lobes, i.e., Broca's and Wernicke's areas (speech and language), bilateral occipital lobes (vision), bilateral parietal lobes (sensation), and bilateral motor cortex (movement).

Cortical mapping may also be done to attempt to identify an epileptogenic focus so that surgical excision or ablation of that area can be accomplished. The goal of complete resection of an epileptogenic focus must often be limited by sparing of eloquent cortex in order to avoid new and unacceptable deficits following epilepsy surgery. Although the homunculus diagram can provide a general idea of where specific motor or sensory functions are likely to be found in the cortex, intraoperative brain mapping provides much more specific information for a particular patient at that specific time of the surgical procedure. As suggested earlier, there are two broad areas of neurosurgery in which intraoperative cortical mapping is employed: excision of intracranial tumors and surgery to treat seizures.

Indications

Application in Cortical Tumor Excision

As already noted, anatomic appearance does not clearly and precisely identify areas of cortical brain tissue subserving a particular function. Multiple studies have shown that long-term prognosis is improved by more extensive tumor excision [7–10]. The use of intraoperative cortical mapping by electrical stimulation of specific anatomical areas provides the neurosurgeon with a real-time and patient-specific functional map. When using cortical mapping to identify eloquent cortex for tumor excision, the concept of positive mapping in contrast to negative mapping also comes into play.

A positive mapping occurs when eloquent areas are identified around the site of planned tumor excision. In other words, specific stimulation sites result in a recognized sensory or motor activity, and these sites are in close proximity to the area of resection of the neural tissue. A negative mapping occurs when electrical stimulation of a surrounding area does not produce any recognizable motor or sensory activity [11–13].

Although it would be easy to think that a positive identification of an area subserving a particular motor or sensory function would be desirable and would allow the surgeon to more precisely navigate the resection around it, experience has shown exactly the opposite. A negative mapping result around eloquent areas seems to provide a better "safe margin" for tumor resection with a low incidence of postoperative neurological defects [14]. In fact, positive identification of eloquent areas around the planned site of tumor resection actually increased the risk of postoperative deficits, probably indicating close proximity of tumor to functional cortex.

Application in Epilepsy Surgery

ECoG is employed in epilepsy surgery in an attempt to identify and remove the "epileptic zone" of tissue. This "epileptic zone" is felt to be the anatomical site of seizure onset as well as the surrounding tissue which might potentially be recruited into the critical mass of tissue involved in the seizure. Although this technique essentially records the same type of electrical activity as an EEG, the electrode montage being placed directly onto the brain tissue, there is less attenuation and dispersion of the electrical signals. This is felt to provide more precise localization of the aberrant electrical activity causing the patient's seizures than a diagnostic EEG.

ECoG requires the presence of a neurophysiologist interpreting the data in real time. Unlike other aspects of intraoperative monitoring, this cannot be accomplished through remote monitoring or telemedicine. The neurophysiologist must remain in close communication with the surgeon. A standard 16-channel EEG machine can be used to do the recording, but since the electrodes are directly on the brain, modifications from the normally used EEG settings of the recording sensitivities, time constants, filters, etc. are made. The machine is usually present in the operating room itself or in an operating room gallery with a two-way communication system in place so that the surgeon and neurophysiologist can communicate.

In order to accurately locate the epileptogenic area, the recording electrodes should be placed at equal distances from each other, both horizontally and vertically on the cortical surface. Angulated electrode placement should be avoided, since this can lead to false localization. Montages should contain at least four electrodes in a straight line.

Actual ictal events are rarely recorded. Instead, usually only interictal epileptiform activity is noted intraoperatively. The area of maximum epileptiform activity is felt to be the irritative zone that initiates the seizure, but this is not necessarily the area of origin of the epileptic seizure. Alacorn et al. found that removal of this area of maximal epileptiform activity yielded a better chance of good surgical outcome with reduction in epileptic activity, but if the area of maximal discharging was not completely resected, surgical outcome was likely to be poor.

Electrical stimulation of a suspected cortical area has been attempted but without good results in localizing the area of epileptogenic activity. When the stimulated area correlates with eliciting the typical aura preceding the seizure and this coincides with the area of greatest epileptic discharge, there seems to be a better correlation with successful surgical treatment of the seizure activity when that area is resected. However, if afterdischarges occur, the correlation to the epileptic zone is not as strong. This is probably due to afterdischarges originating from a distant and uninvolved area.

After surgical resection, sometimes residual spiking activity will occur. Unfortunately, the significance of this is not clear. While 75% of patients who were not seizure-free following resection had residual spikes noted on electrocorticography, 36% of patients who were seizure-free following surgical resection also exhibited residual spikes [15].

Anesthetic Considerations

Most anesthetic agents affect electrocorticography. So, for ideal intraoperative monitoring, the most reliable monitoring results when little if any anesthetic agents are used. Today's anesthesiologists have at their disposal multiple short-acting medications that can be used for sedation, analgesia, or inducing general anesthesia. This coupled with airway technologic advancements has made intraoperative control safe and easy for most patients. Because of this progress, many cases with intraoperative cortical mapping are anesthetized using the "asleep–awake–asleep" technique. This allows the patient to be awake, during the surgical procedure on the eloquent centers of the brain, thus allowing the surgeon to monitor the neurological status of the patient and maximize surgical resection. This technique is more commonly used during procedures such as speech mapping and epilepsy surgery when feedback from the patient is most important. Mapping of primary sensory and motor areas is generally not performed with an awake craniotomy as EMG monitoring can be done with the patient asleep thereby minimizing patient stress, airway complications, and coincident seizures.

General Anesthesia

For sensorimotor mapping with the patient under general anesthesia, a total intravenous anesthesia regimen using propofol and narcotics is preferred. Neuromuscular blockade should be avoided. This regimen preserves the specificity of motor mapping while reducing the incidence of seizures in response to cortical stimulation. Although the use of propofol reduces the incidence of seizures, it does not eliminate the risk, and the team should be prepared to treat an intraoperative seizure if it occurs. The placement of bilateral soft bite blocks (as would be done for MEP monitoring) is also important.

Awake Craniotomy

A successful intraoperative course for an awake craniotomy starts with the preoperative evaluation. Medications should be noted, as well as concurrent medical conditions and serum levels of any antiseizure drugs currently being taken. A

history of complications from medical management of seizures should also be discussed.

The patient should be given a detailed account of expected intraoperative events and warned of certain intraoperative events, such as opening the dura that may cause some discomfort. The anesthesiologist must reiterate the advantages of the patient being awake and ensure the patient that he/she will be present throughout the operation minimizing anxiety and pain when possible. Therefore, constant intraoperative communication with the neuroanesthesiologist will be expected. Lastly, induction and emergence from anesthesiology should be discussed with the patient.

Intraoperative: Local Anesthetics

Intraoperatively, the anesthesiologist and neurosurgeon use local anesthesia to perform regional, field, and dural blocks. Cutaneous nerves branching from the trigeminal nerve innervate the skin, scalp, pericranium, and periosteum. Subcutaneous infiltration with lidocaine or bupivacaine with epinephrine is commonly employed and successful in blocking afferent input to these areas. The skull has no sensory innervation, so it can be drilled and opened with no patient discomfort. The dura receives innervation from all three divisions of the trigeminal nerve, the recurrent meningeal branch of the vagus, and by branches of the upper cervical roots and can produce significant discomfort for the patient when instrumented by the surgeon. Local application by the surgeon can work; however, if this becomes too unpleasant for the patient, then general anesthesia can be induced and a laryngeal mask airway inserted until exposure is completed.

Intraoperative Sedation

Current techniques commonly use propofol, fentanyl, remifentanil, or dexmedetomidate. Many use propofol infusions with slow and careful titrations of fentanyl. Most recently remifentanil has replaced fentanyl due to its ultrashort action and is combined with propofol to provide sedation and analgesia during awake craniotomies. This technique is popular because of the safety profile and lack of respiratory depression if carefully titrated. Dexmedetomidate, an alpha-2-adrenoreceptor agonist, has gained popularity due to its ability to provide analgesia and sedation, which is easily reversed with oral communication. Additionally, it produces no respiratory depression when used alone. Ensuring sedation and analgesia for the patient while preventing apnea or airway obstruction is the main concern for the anesthesiologist. Airway equipment (oral and nasal airways, laryngeal mask airways, and emergency intubation equipment) must be readily available throughout the case.

Asleep–Awake–Asleep Technique

Propofol and remifentanil are the two agents used most frequently for this technique. Both are short-acting, safe, and predictable. Additionally, they can be titrated while using the bispectral index monitoring system, which provides the anesthesiologist more precision for drug dosing adjustment. A laryngeal mask airway is commonly inserted to prevent airway obstruction. With proper propofol and remifentanil dosing, airway irritation is alleviated and neuromuscular blocking agents are not warranted. After the craniotomy is completed and the dura is opened, the remifentanil dose is reduced or stopped, and spontaneous respirations are allowed to resume. The propofol infusion is reduced, and the LMA is removed as the patient regains consciousness. After surgical resection is completed, the infusions are reinstated and the LMA placed until surgery is completed.

Contraindication to Awake Craniotomies

Multiple issues must be considered before proceeding with an awake craniotomy. The ability to communicate with the surgeon and anesthesiologists is imperative. Any communication

problems, such as dysphasia, are strong contraindications for awake craniotomies. Extremely anxious patients or patients prone to an exaggerated pain response should probably be avoided as are patients requiring prone positioning for surgery. Patients with lesions requiring extensive dural surgical resection should probably be avoided. Finally, lengthy surgical procedures may make it difficult for patients who are required to lie still.

Conclusion

It is now recognized that the area of the brain responsible for written and verbal communication varies with each individual. To fully understand the impact of surgical resection, the surgeon should insist on intraoperative cortical mapping. When intraoperative cortical mapping is employed, the surgeon can maximize surgical resection and minimize postoperative disabilities for the patient. Advancements in anesthetic pharmacologic agents and anesthetic equipment have allowed patients to undergo mapping and resection with minimal discomfort while being awake and continuously checked for neurologic interval changes.

Review Questions

1. What are the two most common techniques for cortical stimulation when mapping? How do they differ?
2. How is the central sulcus identified intraoperatively?
3. What is ECoG and when is it used?
4. What are the contraindications for awake craniotomy?
5. What is the difference between positive and negative mapping, and which produces a more favorable surgical outcome?

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19 Neuromonitoring in the Pediatric Patient

Jonathan A. Norton

Introduction

It is a truism that children are not just little adults. When a child comes for a surgical procedure, there are often additional pressures compared to an adult. For the neuromonitoring team involved in the care of a child, there are concerns and challenges related to the case that are pediatric-specific. In this chapter, the unique features of the pediatric patient and some surgical procedures that are pediatric-specific (or more common in the pediatric population) are considered. Although pediatrics is an important part of medicine and surgery, there are few textbooks on the neurophysiology of this population [1, 2] and even fewer on surgical neurophysiology.

Differences

The pediatric patient comes in a variety of sizes; the newborn baby is very small, while the older teenager is adult-sized. In Fig. 19.1 the average size spread of a newborn to adult is illustrated. There are periods of rapid growth (infancy, puberty) interspersed with periods of slower growth. The interested reader is referred to any textbook on pediatrics for more detail on the growth patterns [3]. At a simple level, the small size of infants makes placement of needles more tricky, especially as extra small needles are not typically available. The most difficult needles to place are those for the bulbocavernous reflex (BCR), typically involving stimulation of the dorsal penile or clitoral nerve. In the infant (especially female), these organs can be very small. As the child ages and grows, placement of needles gets a little easier because of the increased size.

When working with an adult, it is often possible to work in parallel with anesthesia and nursing, but in the smaller patients, this is not typically possible. This can lead to the setup taking a longer time than usual. The reduced size of the very young patient also means that they lose heat more quickly and so additional care will be needed to maintain body temperature. Low body temperature is associated with many negative surgical outcomes, including blood loss and infection [4]. Care should be taken to ensure that the patient therefore is covered as much as possible during needle placement. Such care will give you many points with nursing and anesthesia staff and be good for the patient.

In addition to being smaller than adults, the other major difference between adults and pediatric patients that applies to neuromonitoring is the degree of myelination in the nervous system and hence the conduction velocity. Unmyelinated

J. A. Norton (✉)
Royal University Hospital, Department of Neurosurgery, Saskatoon, SK, Canada
e-mail: j.norton@usask.ca

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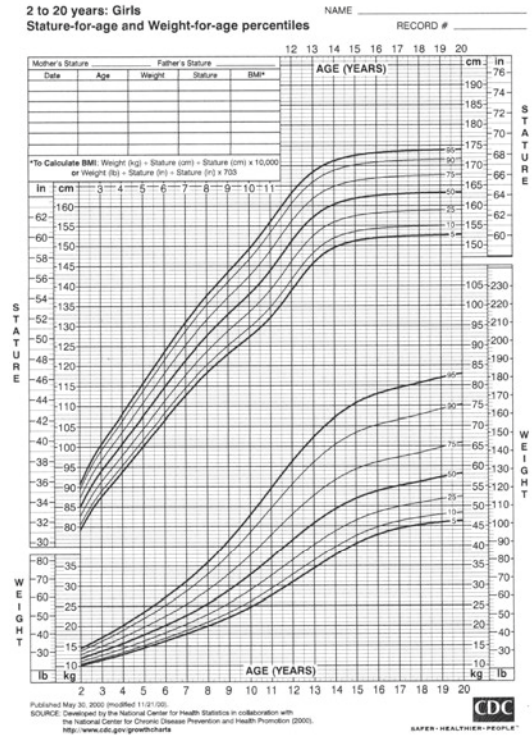

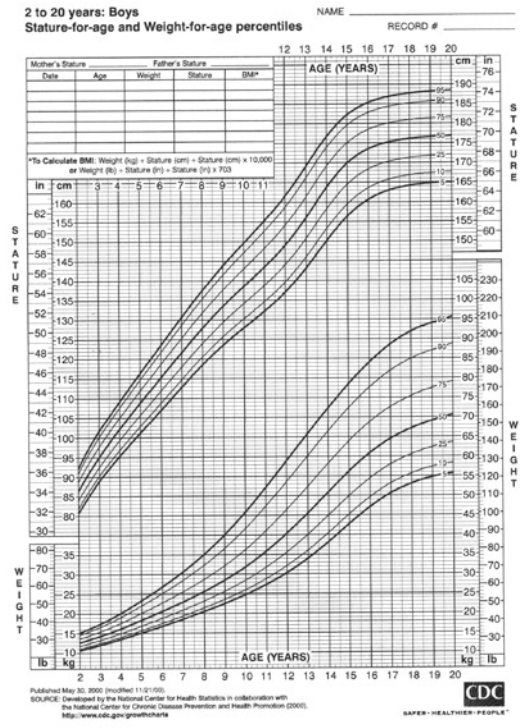

Fig. 19.1 The CDC growth charts for girls (left) and boys (right) from age 2 to 20 for both height and weight. Although these are typical curves, many pediatric surgical patients will fall off these curves. Graphs from Centers for Disease Control and Prevention (www.cdc.gov). Note that these are US curves; each country will have slightly different graphs

fibers conduct more slowly than heavily myelinated fibers; the myelination allows for saltatory conduction. The myelination is not fully complete until around the age of 20, and so the conduction velocity changes throughout the pediatric period. As the size increases and the conduction velocity increases, ultimately conduction delay for evoked potentials changes relatively little. The most comprehensive study on the maturation of the human nervous system comes from the work of Dr. Eyre in Newcastle, UK [5, 6]. The studies showed that there is only a small variation in the central conduction delay in both motor and somatosensory pathways once an infant reaches the age of 2 through to adulthood. There is a significant increase in the conduction velocity with age (Fig. 2 in [7]). These changes are related to axon diameter and myelination. Although there is substantial growth during puberty, the MEP latency is typically very close to mature (adult) values around the age of 5–9 years (Fig. 1 in [8]) [9]. Although these figures are from the recording of MEPs using transcranial magnetic stimulation, they hold for transcranial electrical stimulation and, in general, also for the SSEPs.

Anesthetic Issues

The pediatric anesthesiologist will be critical in obtaining good neuromonitoring [10] even more so than in adult patients. Providing a robust, safe anesthetic in infants is challenging, especially in the face of neurological issues that may be the surgical trigger. In particular, the blood volume in an infant is smaller, and so any blood loss is more significant. This can lead the anesthesia team to wanting to run the patient a little hypotensive, which can cause additional issues

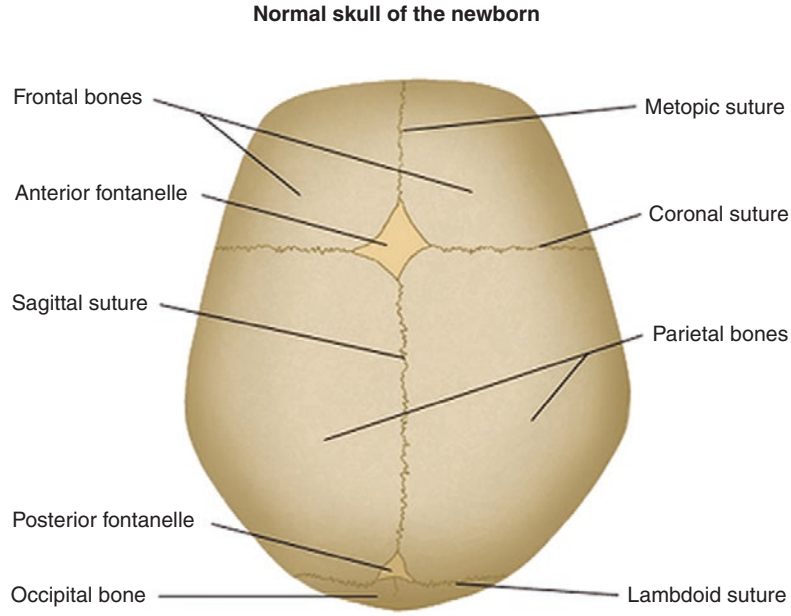

Fig. 19.2 The fontanelles at birth are open and close slowly over the first year of life. They can be palpated to determine their size and location in an individual child to ensure that electrodes are not placed directly over the fontanelle. Even with an open fontanelle, a corkscrew electrode will not reach deeper than the bone

with neuromonitoring. The anesthesia team may also be more reluctant to run a TIVA-type anesthetic. Propofol is a lipid-based anesthetic, and the fat distribution in infants is different than that in older children and adults, making the depth of anesthesia more difficult to predict.

A further consideration that is often at the forefront of the neuromonitorist's mind when dealing with infants are the fontanelles, which are open until about 9–12 months of age (Fig. 19.2). These are gaps in the bones of the skull (which allow for movement of the bones during vaginal birth). When performing MEPs, the voltages used are often very high (<300 V). These voltages are used because the bone is highly resistant and most of the voltage is shunted extracranially. When the skull is not intact, there is a much lower resistance pathway to the cortex. However, it should be remembered that direct cortical stimulation can be used, although the currents are much lower than transcranial stimulation. My personal approach is to firstly ensure that the stimulation electrodes are not placed over the sutures and then the stimulation voltage is slowly increased until MEPs are seen. When placing electrodes for SSEPs care is also taken to avoid the open sutures.

Surgical Procedures

Although children can have some of the same conditions that require surgery as adults, they also have some unique conditions. Myelomeningocele, scoliosis, and posterior fossa tumors are probably the three most pertinent for neuromonitoring.

Myelomeningocele

More commonly known as spina bifida, myelomeningocele is usually detected before birth and so the surgery is typically scheduled [11, 12]. When the neural tube is open and uncovered, closure of the defect is an urgent procedure. If the tube is partially covered, then the procedure may be delayed a little. The goal of the surgery is to close the neural tube and untether the spinal cord and nerve roots if needed. Root stimulation may be needed to identify roots and assist in placing them correctly in the canal [11, 13]. Motor evoked potentials can be used to determine which spinal levels are under (or will be under) voluntary control. Because these patients are likely to require many subsequent surgeries (neurosurgical,

orthopedic, etc.) [14] and may need to be catheterized long-term, it is advisable to treat them as latex sensitive, and so avoid using latex-based electrode fixation.

Spine Deformity

Much of the history of neuromonitoring is tied up with the monitoring of pediatric spine deformity surgery [15–17]. Many of the same considerations in adult spine surgery apply in pediatric surgery. Typically, however there is no use of interbody fusion devices, and often the fusion and instrumentation extend over a longer portion of the spine than is seen in adults. In idiopathic scoliosis, the patients are typically healthy, and predominantly female [18]. I am always a little more cautious when approaching a male with idiopathic scoliosis that is severe enough to warrant surgery. In addition to the idiopathic form, there are many non-idiopathic forms of scoliosis or other spine deformity, neuromuscular scoliosis, and infantile scoliosis presenting the most challenges in terms of monitoring. The neuromuscular form is often a gentler curve than other forms, but it arises because of a lack of voluntary motor control over the axial muscles, and so challenges in long-tract evoked potentials are to be expected. The infantile form may be treated by serial casting or bracing or non-fusion spine surgery using a growing construct. It is debatable whether monitoring is needed when these devices are lengthened [19]; however, it is our practice to monitor these cases, although with less channels than a typical fusion procedure.

Posterior Fossa Tumors

Tumors of the posterior fossa are by no means unique to children; however they do have different tumors than adults in that space. Intramedullary brainstem tumors are particularly aggressive in the pediatric population and often present to the neurosurgeon relatively late after being investigated for other causes of nausea, vomiting etc. The principles are the same as with adults; the tumor is approached at the point at which it is closest to the pial surface. Brainstem mapping is used to identify a "safe" entry zone avoiding the nuclei in the brainstem. For this to be successful, there must be good EMG recording from all of the muscles innervated by the nuclei [20–22]. Around the smaller muscles (eye, mouth), it can be tricky to accurately place electrodes if needles are used, and so to truly isolate the muscles, a small wire electrode should be used. Although the focus is on brainstem and cranial nerve monitoring, there remains a role for monitoring the long tracts that pass through the brainstem using both somatosensory and motor evoked potentials [23].

Tips and Tricks

The MEP is the most difficult potential to record in all patients, and especially in the pediatric population, more so in the neonate. The lack of myelination in the corticospinal tract can add further difficulties to these potentials because the potentials may reach the anterior horn cells at different times reducing the likelihood of a MEP in the muscle being triggered. My approach is to try using both double trains and longer inter-pulse intervals in an attempt to get as many action potentials arriving at and depolarizing the anterior horn cells.

The ABR is a relatively easy potential to record in neonates, and the SSEP while a little harder is still easily recordable using similar parameters to that used in adults.

Review Questions

1. What are two anesthetic considerations when monitoring the pediatric patient?
2. If the monitorist is having difficulty obtaining MEP recordings in the pediatric patient, what might they try?
3. Why are MEPs harder to obtain in young children?
4. What precautions should be taken when placing scalp electrodes in the pediatric patient?

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20 Neurological Assessment and Correlation in Spinal Cord Nerve Root Pathology

Alan David Kaye, Mark R. Jones, Mark W. Motejunas, Ken P. Ehrhardt Jr., and Joseph H. Feinberg

History

Patients may complain of weakness, pain, or numbness and tingling in one or more extremities. Important points to discuss with patients during their initial visit include the location and character of their symptoms, how and when it started, if there are any exacerbating or relieving factors, whether it is continuous or intermittent, and how certain position affects the symptoms. Psychosocial factors can also play a significant role in how patients experience pain. Therefore, it is necessary to also ask questions about how stress affects the pain, whether there is a concomitant sleep or mood disorder, how pain affects the patient's function at work or school, and how the pain affects quality of life. Furthermore, a patient's motivation for evaluation must be clarified early. If there is possible litigation involved, it can affect how patients portray and describe their pain.

Physical Examination

The physical examination begins as soon as the patient walks in the door. Clinicians will take note of how patients walk, sit down, get up, and what their posture is like. Whether a patient exhibits ataxia, walks with a limp, or must use a cane or walker to ambulate provides important information. Take note of the patient's overall appearance, including weight and muscle bulk, masses, and signs of injury. Are there differences in the skin, nails, hair, and temperature of the limbs? Look at the spine for the presence of scoliosis, kyphosis, and loss of curvature.

Motor Examination

There are several steps that make up the motor examination. With each assessment, it is important to compare the left and right sides. First, the examiner should observe the patient to detect any signs of a movement disorder, such as twitches or tremors, which are usually associated with lesions of the basal ganglia and cerebellum. The

A. D. Kaye (✉)
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

M. R. Jones
Harvard Medical School, Beth Israel Deaconess Medical Center, Department of Anesthesia, Critical Care and Pain Medicine, Boston, MA, USA

M. W. Motejunas · K. P. Ehrhardt Jr.
Louisiana State University School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

J. H. Feinberg
Hospital for Special Surgery, Department of Physiatry, New York, NY, USA

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patient's posture when he or she walks into the room and sits down should also be noted. An abnormal position may be indicative of weakness. The examiner also inspects the muscles for signs of wasting, fasciculations, or hypertrophy, which can be followed by measuring the circumference at a specific location. Additionally, the examiner may palpate muscles to detect any tenderness. Muscle tone is tested by instructing the patient to relax while the examiner passively moves a joint through normal range of motion, feeling for any rigidity or flaccidity. One should also look for asymmetry when comparing the upper and lower limbs.

It is important to distinguish actual muscle weakness from pain-limited strength and lack of effort. A specific pattern of weakness can help to localize a lesion. Many clinicians will test a muscle group on one side of the body and then test its contralateral counterpart to enhance detection of any asymmetries. As well, asymmetrical findings can be of significant value. It is also important to be aware of differences in proximal and distal muscle strength. In general, muscles do not work in isolation, and therefore, the scale really is better used in order to describe a motion per se, rather than an isolated muscle, for example, elbow flexion versus biceps strength. At any rate, muscle strength is usually rated on a scale of 0–5 (Table 20.1).

While muscles often work in synergy to create in aggregate a given motion, they rarely work in isolation. Nonetheless, to test the deltoid muscles, which are innervated primarily by the C5 nerve root and to a lesser extent the C6 nerve root, patients simultaneously raise both arms in front of them as the examiner provides resistance to this movement. The biceps muscles are innervated by the C5 and C6 nerve roots. To test the strength of the biceps, hold the patient's wrist from above and provide resistance and instruct him or her to flex the hand up to the shoulder. Next, test the triceps muscle strength. Patients should start from a fully flexed position and extend their forearm against resistance provided by the examiner. The triceps muscle, the major elbow extensor, is primarily innervated by C7 nerve roots and to a lesser extent a C6 and a C8 (long head of the triceps) component. Wrist flexion is predominantly C7, and to a lesser extent, C6 can be tested by having the patient flex their wrist. Wrist extensors are innervated predominantly C6, and to a lesser extent, C7 nerve roots can be tested by having patients extend their wrists while the clinician is providing resistance. Examine the patient's hands for signs of thenar and hypothenar muscle wasting. To test grip strength, ask patients to make a tight fist around the examiner's fingers and instruct them to not let go as the examiner tries to remove them. Grip strength is a test of intrinsic hand muscles and finger flexion, which is innervated by the C8 nerve root. Thumb abduction, which is primarily innervated by the T1 nerve root and to a lesser extent C8, is tested by having patients abduct the thumb. Thumb opposition is innervated by the C8 and T1 nerve roots and is tested by having patients touch the tip of their thumb to the tip of their pinky finger as the clinician is applying resistance to the patients' thumb. The trapezius, rhomboid, and serratus anterior muscles are difficult to test in isolation. Therefore, it is important to look at scapulothoracic motion and dynamics, and one should observe for the presence of scapular winging. This will help identify deficits in any of these scapulothoracic muscles.

Hip flexion is tested by having the patient lie supine and raising each leg separately as the examiner is providing resistance. Hip flexion is innervated by the L2 and L3 nerve roots and tests the iliopsoas muscle. The L2, L3, and L4 nerve roots provide innervation for adduction of the hip. Hip adduction is tested by the examiner placing his or her hands on the inner thighs of the patients and instructing them to bring both legs together. The gluteus maximus and gluteus mini-

Table 20.1 Muscle strength grading scale

0	No muscle contraction
1	Slight contraction but no movement
2	Movement is possible when gravity eliminated (test in horizontal plane)
3	Movement is possible against gravity but not against resistance; moderate weakness
4	Movement against gravity and some resistance; slight weakness
5	Full range of motion against gravity and resistance; normal strength

mus muscles are tested by having the examiner's hands on the patient's outer thighs and providing resistance while the patients move their legs apart. Innervation for this movement comes primarily from L5, and S1 nerve roots, and to a lesser extent the L4 nerve root. Extension of the hip is tested by having the patient lie supine with one leg raised, the examiner placing a hand under the patient's thigh and then instructing the patient to press down on the examiner's hand. This tests the gluteus maximus, and innervation comes primarily from the L5 and S1 nerve roots. The L3 and L4 nerve roots provide innervation for knee extension by the quadriceps muscle. Extension at the knee can be tested by the examiner placing a hand on the anterior surface of the lower leg to provide resistance and having the patient "kick out." This movement tests the quadriceps muscle, and innervation is provided by the L3 and L4 nerve roots. The hamstring muscles are innervated by the L5 and S1 nerve roots, which allow for flexion at the knee. Test flexion at the knee by placing a hand on the pack of patients' calves and instructing them to pull the lower leg back. Dorsiflexion of the ankle is tested by placing a hand on top of the ankle and having patients pull their foot up toward their face as the examiner is applying resistance. This tests muscles in the anterior compartment of the lower leg, and innervation comes primarily from the L5 and sometimes the L4 nerve root. Next, hold the bottom of the patient's foot to provide resistance and instruct them to "step on the gas pedal" to test the gastrocnemius and soleus muscles. This ankle plantar flexion receives innervation from the S1 and S2 nerve roots. To test the extensor hallucis longus muscles, which are innervated by the L5 nerve root, ask the patient to move the large toe up toward the patient's face while providing resistance.

Deep Tendon Reflexes

When a muscle tendon is tapped, the muscle will normally immediately contract. Hyperactive or clonic reflexes (3+ or 4+) are suggestive of an upper motor neuron lesion consistent with a disruption in the descending corticospinal tract or at a higher level. Hypoactive reflexes (0 or 1+), on the other hand, can be caused by lesions in lower motor neurons, muscles, sensory neurons, and neuromuscular junctions. Arthritis or any contracture of a joint can mechanically lead to diminished reflexes. The grading scale for deep tendon reflexes (DTRs) is shown in Table 20.2.

Table 20.2 Deep tendon reflex grading scale

0	No response; abnormal
1+	Trace response; may or may not be normal
2+	Average response; normal
3+	Very brisk response; may or may not be normal
4+	Clonus; always abnormal greater than 2 beats

The biceps reflex tests the C5 and C6 nerve roots. The patient's arm is partially flexed at the elbow, and the examiner places a finger over the biceps tendon and then strikes his or her finger with a reflex hammer. The brachioradialis reflex also tests the C5 and C6 nerve roots. Position patients with their arm bent at the elbow and resting on their thigh. When the tendon is struck approximately 3 in. proximal to the wrist, the muscle will contract and the arm will supinate. The pronator teres reflex, which reflects the C7 nerve root level, is tested with the elbow bent at 90°. The forearm is positioned at a neutral position and the distal radius is tapped anteriorly, eliciting a reflex response. To test the triceps reflex, which is mediated by the C7 and C8 nerve roots, the clinician can hold the patient's arm at the antecubital fossa and instruct the patient to let the arm hang loosely 90° at the elbow. The examiner then strikes the tendon proximal to the olecranon. The normal response is contraction of the triceps muscle with extension of the elbow. To reinforce testing of deep tendon reflexes in the upper extremities, the examiner may ask the patient to clench their teeth. This maneuver will distract patients in the case of the examiner having difficulty eliciting reflexes.

There are two deep tendon reflexes in the lower extremity that are commonly tested—patellar and Achilles. The patellar reflex ("knee jerk") is mediated via the L3 and L4 nerve roots. The patellar tendon is usually visible and palpable below the kneecap. The patient should be sitting on the edge

of the examination table with the lower leg hanging freely, and when the tendon is struck, the normal reflex is for the quadriceps muscles to contract, causing extension at the knee. The hamstring reflex can be used to test the L5 nerve root level. The patient lies on their side with the knee flexed 90°. The medial distal hamstring tendon is tapped to elicit a response. The S1 and S2 nerve roots mediate the Achilles reflex ("ankle jerk"). To elicit this reflex, the patient's lower leg should be hanging freely over the edge of the examination table and the examiner should hold the foot at 90°. Striking the tendon with the reflex hammer should cause contraction of the gastrocnemius muscle and plantar flexion of the foot. The Jendrassik maneuver helps to reinforce testing of deep tendon reflexes in the lower extremities. This is accomplished by having patients flex all of their fingers, hook them together, and pull apart.

Sensory Examination

The sensory examination of the extremities assesses the spinothalamic and dorsal column afferent pathways. The spinothalamic tract consists of nerves that detect pain, temperature, and crude touch. The nerve fibers course from the periphery to the spinal cord, where they cross over to the other side within one or two vertebral levels of where they enter. The fibers then continue their course up to the brain and synapse in the cerebral hemisphere on the opposite side of the body from where they originally began. To test a patient's ability to sense sharpness, many clinicians will break a cotton swab in half to create a sharp end. Ask patients to close their eyes so as to not allow them to be distracted by visual clues. Alternately touch the patients with the sharp end and the cotton end in specific dermatomes, and ask them to state whether they are feeling a sharp or dull sensation. Patients should also note if they experience a difference in sensation on each side of the body. To test particular dermatomes, the examiner should touch the patient in the areas shown in Table 20.3.

Table 20.3 Dermatomal sensory distribution

Posterior aspect of shoulders	C4
Lateral aspect of upper arms	C5
Tip of thumb	C6
Tip of 3rd digit	C7
Tip of 5th digit	C8
Medial aspect of lower arms	T1
Upper and lateral part of thigh	L2
Lower-medial aspect of thigh and patella region	L3
Medial leg	L4
Lateral leg and first toe	L5
Sole of foot and the 5th toe	S1

Temperature sensation is also carried by the spinothalamic tract. In the office setting, this is often done with a metal object, which feels cold on the skin. As with testing for sharp sensation, touch the patient at specific dermatome areas. The findings on this examination should corroborate those of the sharp stimulus testing.

Proprioception and vibration sense are mediated through the dorsal columns of the spinal cord. Unlike the nerve fibers of the spinothalamic tract that cross over to the contralateral side, the nerves of the dorsal columns course up the spinal cord on the same side and then course over at the brainstem. Proprioception is the ability of the body to know where it is in space, which aids in the ability to balance. The examiner can test proprioception by holding the patient's big toe on the sides, moving it either up or down, and asking the patient which position it is in. The patient's eyes should be closed during this maneuver so as to not receive any visual hints. If the patient is not able to correctly identify the position of the toe, then the examiner should move more proximally, such as to the ankles, and repeat the test. Similar testing may also be done in the upper extremities at the fingers, wrists, and elbows.

Vibratory sensation is also mediated by the dorsal columns of the spinal cord, so the results should verify the findings of the proprioception testing. Generally, the examiner starts by having the patient seated and places a vibrating tuning fork on top of the interphalangeal joint of the

great toe and also places two or three fingers from the other hand on the bottom side of this joint. The examiner should be able to feel the vibrations transmitted through the joint with his or her fingers. The patient should be able to determine when the vibrations cease, which the examiner should also be able to feel.

Nerve roots can be damaged as they branch off from the spinal cord. For example, herniated disc material or tumors can compress the nerve roots, which will result in a sensory deficit in its distribution. The examiner should be able to identify the deficit on examination. The sensory examination can be altered by the presence of diabetes mellitus, thiamine deficiency, and neurotoxin damage.

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21 Electrophysiological Assessment of Spinal Cord Pathology in Pain Medicine

Amit Prabhakar, Alan David Kaye, Aaron J. Kaye, and Justin E. McKone

Introduction

Electrophysiologic testing plays a pivotal role in the recognition and assessment for both central and peripheral nervous system dysfunction. Electrophysiological tests can provide information about the severity and chronicity of a neurologic problem that radiographic studies like magnetic resonance imaging (MRI) or computed tomography (CT) cannot provide. These tests are helpful in establishing whether an abnormality seen on radiographic images is even truly clinically significant. More importantly, electrophysiological tests can also detect abnormalities not seen on radiographic images, allowing for more specific and precise treatment plans. This chapter will discuss the different modalities available for electrophysiologic assessment of the spinal cord.

Nerve Conduction Studies

Motor Nerve Conduction Studies

The basis of motor nerve conduction studies is that a nerve is electrically stimulated while multiple parameters are concurrently measured to determine how well the nerve transmits an impulse. One electrode is placed over a muscle and a second electrode is placed over the tendon insertion of that muscle. The examiner stimulates the nerve at a certain distance from the muscle, and the evoked response is recorded. Latency is defined as the time from stimulation of the nerve until the evoked response, which represents depolarization of the muscle, occurs. The examiner will then stimulate the nerve at a more proximal site, and the latency at this site is also measured. The velocity of conduction between these two points is calculated by dividing the distance between them by the difference between the latency of the distal stimulation site and the latency of the proximal stimulation site. However, the conduction velocity from the distal stimulation site to the muscle cannot be determined because of intrinsic delays at the neuromuscular junction [1].

A. Prabhakar
Emory University School of Medicine, Department of Anesthesiology, Division of Critical Care, Atlanta, GA, USA

A. D. Kaye (✉)
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

A. J. Kaye
Department of Anesthesiology, Medical University of South Carolina, Charleston, SC, USA

J. E. McKone
Lousiana State University School of Medicine, New Orleans, LA, USA

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The F wave is also measured in motor nerve conduction studies. When a nerve is stimulated, the axon depolarizes not only distally but also proximally. The distal depolarization causes the evoked response discussed above, while the proximal depolarization travels to the spinal cord via antidromic conduction of alpha motor neurons. Anterior horn cells are then activated, and the impulse travels orthodromically to depolarize the muscle, which is the F response. The F response can be variable and is a test of motor function only. They are helpful in determining if there is a disturbance in the function in the proximal nerve. For example, if distal nerve conduction studies are normal but the F wave latency is prolonged, there may be a lesion of the proximal nerve [2].

Sensory Nerve Conduction Studies

An active electrode and a reference electrode are placed over the nerve being studied, and the nerve is stimulated either proximally or distally to the electrodes. If stimulated proximally, antidromic conduction occurs. If the nerve is stimulated distally, orthodromic conduction occurs. The time from the onset of the stimulus to the onset of the action potential is measured and is divided by the distance between the two electrodes. This value represents the sensory conduction velocity [3].

When the nerve conduction velocity is decreased, it is usually due to a disorder of the myelin, but this may also be seen in disorders affecting larger axons. Dysfunction of the axons more commonly causes a decrease in the amplitude of evoked motor and sensory responses because fewer fibers are able to conduct the response [3].

Reflex Studies

In reflex studies, a sensory nerve is stimulated and a motor response is recorded and measured. The H reflex is described as the electrical counterpart to the muscle stretch reflex of the ankle jerk. The posterior tibial nerve is submaximally stimulated at the popliteal fossa to selectively depolarize the large Ia afferent fibers. The impulse is carried to the dorsal horn of the spinal cord, where it then depolarizes alpha motor neurons in the anterior horn. The impulse travels back to the soleus muscle and causes it to contract. Consequently, the H reflex helps to determine the integrity of both the S1 motor and sensory nerves. While it is most common to evaluate S1 radiculopathies, H reflex testing has also been used to assess C6–C7 lesions by stimulating the median nerve and measuring the response at the flexor carpi radialis muscle. L3–L4 lesions can also be assessed by stimulating the femoral nerve and recording from the vastus medialis muscle [3]. The amplitude of the H reflex is increased after spinal cord injuries. H reflexes are still present during spinal shock even though deep tendon reflexes are lost.

Electromyography

Electromyography evaluates and records electrical changes within a skeletal muscle. In the resting state, muscle fibers have a transmembrane potential of 70–90 mV. The inside of the cell has a negative charge relative to the extracellular space. When a nerve impulse reaches the neuromuscular junction, acetylcholine is released and initiates an action potential that spreads across the muscle fiber and causes contraction. A monopolar needle electrode is commonly used to perform electromyography. It is a wire electrode coated with insulating Teflon, sparing the tip because that is where the recording occurs. The small-diameter needle is inserted into the muscle, and there is a surface electrode on the patient's skin. The needle is attached to an oscilloscope with an amplifier, so electrical activity of the muscle can be observed as waveforms. The examiner can also hear the characteristic sounds of various potential changes encountered.

The examiner will evaluate spontaneous activity of the muscle by instructing the patient to relax the limb as much as possible. Insertional activity is the response that occurs when the needle is inserted into the muscle. A burst of spike potential occurs up to 100–300 ms after the conclusion of needle motion. A prolonged time of insertional activity can be a sign of neuromus-

cular disease, while a decreased insertional activity time may indicate loss of muscle tissue. There is normally no electrical activity in resting muscle. However, there can be normal spontaneous activity if the needle electrode is near a motor end plate. Abnormal spontaneous activity includes fibrillation potentials and positive sharp waves, which are seen if the muscle fiber membrane is electrically unstable. Fibrillations occur when the muscle fiber loses continuity with its motor nerve, thus allowing for spontaneous depolarization. They are associated with lower motor neuron diseases such as radiculopathies, neuropathies, and anterior horn cell pathology, as well as myopathies, hypokalemia, and hyperkalemia. Fibrillations have been reported in cases of spinal cord injury as well, though this is controversial [3]. Positive sharp waves are associated with the same disorders as fibrillations.

Somatosensory Evoked Potentials

Somatosensory evoked potentials (SSEPs) are a technique to evaluate the function of the ascending spinal tract. They are obtained by stimulating a peripheral nerve, usually the median or ulnar at the wrist or the tibial or peroneal at the ankle, and recording the response from the patient's scalp. They are often used intraoperatively to monitor spinal cord function. SSEPs can evaluate the function of the distal and proximal peripheral nervous system, as well as the spinal cord and brain, since the potentials are carried by sensory nerves peripherally and by the dorsal column-lemniscal system centrally. They have been reported to be of some use in determining ambulation outcomes [4]. Iseli et al. discovered that patients with ischemic spinal cord injury had similar motor and sensory deficits as patients with traumatic spinal cord injury. Both groups also had pathological SSEP recordings [5]. It is important to remember that inhalational anesthetic agents decrease response to SSEP. When general anesthesia is needed for testing, total intravenous anesthesia(TIVA) is preferred to limit confounding factors and increase accuracy. A combination of propofol and remifentanil has been shown to cause less decrease in cortical SSEP than desflurane and remifentanil [6]. SSEPs can also be used intraoperatively for neurovascular cases to predict postprocedural neurological deficits and guide interventions during procedures [7, 8]. When SSEP, motor evoked potentials, and nerve conduction studies are added to International Standards for Neurological Classification of Spinal Cord Injury, they provide invaluable information that helps clinicians guide treatment and predict long-term prognosis.

This chapter reviews the most common and relevant modalities available to ascertain potential spinal cord pathology by electrophysiological assessment. When coupled with radiographic findings, electrophysiologic testing increases accuracy and allows clinicians to formulate better treatment plans for patients. Electrophysiologic testing also has the ability to detect neuronal pathology even when gold-standard radiographic studies like MRI do not show obvious lesions. As technology continues to evolve at a rapid pace, novel techniques will continue to improve medical decision-making and enhance patient care.

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Spinal Cord Stimulation: Principles and Applications

22

Ramsin Benyamin, Jay S. Grider, Mark W. Motejunas, Best Anyama, Elyse M. Cornett, David L. Cedeno, Ricardo Vallejo, and Alan David Kaye

Introduction

The concept of electrical stimulation applied for the treatment of pain was first documented in a book published in 47 AD called the *Compositiones* by Scribonius Largus. Largus demonstrated that shock incurred by the torpedo ray induced analgesia for both gout and headaches. A substantial amount of progress has occurred since that time, providing treatment for a wide range of clinical symptoms using various electrical stimulation modalities. There are two clinical applications for electrical stimulation to nerves. The first is designed to treat motor disorders such as tremors caused by advanced Parkinson's disease. The more common use for electrical stimulation uses focused electrical treatment to neural targets resulting in analgesia. Current targets for stimulation include the spinal cord, dorsal root ganglia, and peripheral nerve tracts.

The predominant use of electrical stimulation is spinal cord stimulation (SCS), where direct electrical stimuli are applied to the spinal cord for the treatment of chronic pain. This concept is based on gate control theory by Melzack and Wall [1]. This theory dictates that the stimulation of large beta fibers closes the gate on small fiber transmission resulting in perceived analgesia.

Shortly after gate control theory was introduced, electrical stimulation for the treatment of pain progressed rapidly with the introduction of new devices and applications. In 1967 Wall and Sweet used infraorbital stimulation for the first time. Later that year, the first spinal cord stimulator was implanted by Shealy and Mortimer. One year later, in 1968, Sweet and Wepsic implanted the first peripheral nerve stimulator. The first commercial spinal cord stimulator was introduced by Medtronic in that same year. The

R. Benyamin
Millennium Pain Center, Bloomington, IL, USA

Department of Surgery, College of Medicine, University of Illinois, Urbana-Champaign, Urbana, IL, USA

J. S. Grider (✉)
University of Kentucky Medical Center, Department of Anesthesiology, Lexington, KY, USA
e-mail: jsgrid2@uky.edu

M. W. Motejunas · B. Anyama
Louisiana State University School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

E. M. Cornett
LSU Health Shreveport, Department of Anesthesiology, Shreveport, LA, USA

D. L. Cedeno
Millennium Pain Center, Basic Science Research, Bloomington, IL, USA

R. Vallejo
Millennium Pain Center, Bloomington, IL, USA

A. D. Kaye
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

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standard non-rechargeable batteries were replaced by the first rechargeable battery in 2004 by Advanced Bionics which later became part of Boston Scientific.

Currently, neuromodulation has three primary manifestations: spinal cord stimulation, peripheral nerve stimulation, and intracranial stimulation of the deep brain and motor cortex. There are two major advantages to these therapies: reversibility of treatment and treatment trial prior to permanent implant. The trial of the device allows the patient to test the treatment in a more minimally invasive manner to determine efficacy. The technical goal is to obtain overlap of electrical stimulation on painful areas. The clinical goals are reduction in pain, improved function and quality of life, and reduction in the amount of analgesic pain medication. Indications for the device in the USA are failed back surgery syndrome (FBSS) and complex regional pain syndrome (CRPS). Indications for the device in Europe are ischemic pain caused by peripheral vascular disease and intractable angina.

Spinal cord stimulation is a useful therapy in the treatment of a multitude of pain conditions. A literature review of SCS in FBSS patients revealed that SCS is effective in relieving the chronic intractable pain associated with the syndrome [2]. This type of neuromodulation is also reported to be effective in certain applications for discogenic pain and Reynaud's syndrome by altering sympathetic outflow, resulting in increased blood flow and decreased pain [3]. Neuromodulation is a promising treatment for long-term chronic and neuropathic pain modalities.

Physiology and Biophysics of Neuromodulation

Understanding the physiology behind SCS requires review of basic neurologic functioning at both the cellular and axonal levels. Recall that each axonal cell body in the inactive state has a negative resting potential. Upon activation of the axonal cell body, the inward sodium current increases the resting potential to the threshold potential. Once the threshold potential is reached, an action potential is initiated. This action potential propagates down the axon via salutatory conduction in myelinated axons. However, the basic transduction of the signal from the spinal cord stimulator electrode to the biological system is often poorly understood.

To better comprehend this concept, conduction of electrical signals in nonbiological systems must be understood. In nonbiological systems, electrical current is carried via a conducting medium (in this case, the conductive material in the spinal cord stimulator lead). The electrical current in the SCS lead electrode results in the flow of electrons producing an electrochemical reaction. There are two types of electrochemical reactions: galvanic and electrolytic. Galvanic cells *produce* electrical energy while electrolytic cells *consume* energy. In basic terms, the SCS is a galvanic cell while the biological system is an electrolytic cell. The SCS electrodes have non-insulated regions known as "contacts" that provide the interface between the SCS and biological tissue. This contact is programmed to be either positive (anode or oxidative contact) or negative (cathode or reductive contact). By convention, electron flow is described as moving from the positively charged anode to the negatively charged cathode. This flow of electrons creates an electrical field. It is the size and "shape" of the generated electrical field that clinicians manipulate to produce the desired clinical result with SCS systems [4].

The conduction of electrons in the SCS lead is a Faradaic reaction. A Faradaic reaction is flow of charge electrical (i.e., nonbiological) systems such as wiring. When the electrical field produced by the flow electrons in this electrical system contacts biologic tissue, the energy (galvanic reaction) is converted or transduced into a biological flow of charge. This biologic flow of charge is produced by the movement of the ions in the electrolyte cellular solution and is known as a non-Faradaic process.

For example, an electrode is placed into non-ionic water. The water molecules are electrically neutral but do have regions of charge (positive oxygen/negative hydrogen). When the negatively charged (cathode) is produced, the water molecules move to orient themselves with the positive region of the molecule facing

the negatively charged electrode contact. In an electrolyte-containing solution, the positively charged ions (sodium in the case of the axon) move toward the negatively charged electrons when an electrical field is generated. This movement of sodium creates a regional charge imbalance which, if occurring at the neuronal membrane, alters the resting membrane potential and activates an action potential. This sequence of events transduces the electrical energy of the SCS into an action potential within the sensory fibers of the dorsal columns of the spinal cord [5]. The resulting sensory activation is felt by the patient, and the sensation is described as a *paresthesia*.

This paresthesia, when overlapping the dermatome or region of neuropathic pain, competes with pathologically activated pain pathways within the dorsal horn. Through a complex signal processing and conduction, this sensation reaches the higher brain centers [6]. The dorsal horn acts as a processing station for incoming sensory information. Sensory input such as the sensation of pain and the generated paresthesias are processed simultaneously by the dorsal horn, and the representative sensory input is relayed to the cortex [7]. This process is known as signal convergence. Signal convergence within the spinal cord is utilized by SCS to create an analgesic effect [7]. In essence, the presence of a non-noxious paresthesia produced by the SCS system competes with the noxious stimulus from the pain fibers. As described in the gate control theory of pain, this non-noxious stimulus acts to dampen the painful noxious stimulus at the level of the dorsal horn.

Ohm's law governs the properties of the electrical field generated. The components of Ohm's law, voltage, current, and resistance (and the close corollary impedance), are best thought of regarding fluid dynamics. In this case, voltage is roughly analogous to the force or pressure of water, resistance to the size of the opening through which the fluid moves, and current to the volume of fluid that moves through the opening in a unit of time. Using a garden hose as an example, if the nozzle opening is made smaller (i.e., an increase in resistance) but pressure (i.e., voltage) is held constant, flow or current will decrease. Since the relationship of Ohm's law is $V = I \times R$, when voltage is held constant, an increase in resistance will result in a decrease in flow or current. The other relationships follow similarly.

This is a vital concept, since SCS systems control the (dependent) variables of voltage or current, while resistance (or its close corollary impedance) tends to be a function of the biologic system and, therefore, an independent variable. These considerations are debatable from a clinical standpoint as it is presently unclear if constant voltage or constant current SCS systems provide different clinical results.

Basics of Spinal Cord Stimulator Programming

The electrical field generated and the paresthesia elicited by the electrical field can be customized to patient preference. For example, each "pulsation" or electrical field has an amplitude (or strength of pulsation), a pulse width (how long the pulse lasts), and a frequency rate (pulses per second) (Fig. 22.1). These parameters can be

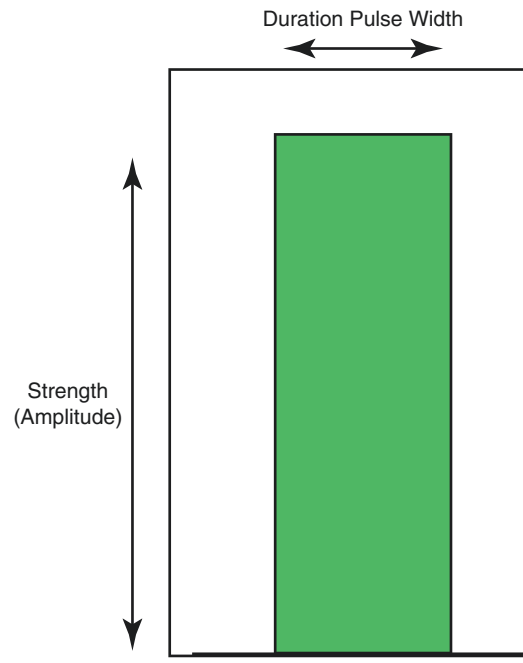

Fig. 22.1 Square pulse commonly used for spinal cord stimulation, which is dependent on amplitude and pulse width

manipulated to alter the perception of the stimulation paresthesia. When a SCS lead is in place over the target tissue, the strength of the pulse is gradually increased until the patient first detects the stimulation. This is called the *perception threshold*. The stimulation may be increased to a therapeutic value and ultimately may be increased beyond the ability of the subject to tolerate the sensation. This is referred to as the *discomfort threshold* or the amplitude (strength) at which the patient no longer tolerates the stimulation. It is important during the trial and implantation phase to carefully determine these parameters, as a subject with a very narrow ratio of perception to discomfort thresholds (i.e., narrow therapeutic range) may describe the stimulator as "shocking" them or decrease use due to dissatisfaction with the paresthesia.

The pulse or stimulation rate can be manipulated to create distinct pulses. Settings of the SCS can vary between a low rate or a merging of pulse sensations with higher frequency stimulation. Lower frequencies result in a more distinct, slower pulse, while higher frequencies result in a more continuous, smoother sensation.

Complex mathematical modeling of the impact of these parameters on SCS function has been done. Named for Jan Holsheimer, the concept of mapping out the proper lead positioning and concomitant SCS parameters for optimal effect has become known as Holsheimer mapping [8]. While they are advanced concepts, the mathematical underpinnings of SCS programming are important issues to understand when complex programming is required. Pulse width provides an illustrative example of this concept. For example, if a spinal cord stimulator lead is placed in a more lateral position within the epidural space, a longer pulse width may activate the spinal cord nerve root and cause discomfort. In this scenario, narrowing the pulse width may be beneficial.

Electrical Field

The shape of the electrical field created is dependent on the configuration of anodes and cathodes. In a simple system using one anode and cathode, charge flows as described above with very little ability to "shape" the contour of the electrical field (Fig. 22.2). Over the last 10 years, the utilization of an electrode combination referred to as a "guarded cathode" has proven useful. This configuration has anodes on either side of the negative cathode setting up an electrical barrier to the spread of the electrical field, driving the field in a targeted fashion (Fig. 22.3). This concept is important to successful trialing of SCS as the ability to "steer" current toward the target areas of pain determines the ability to produce the overlapping

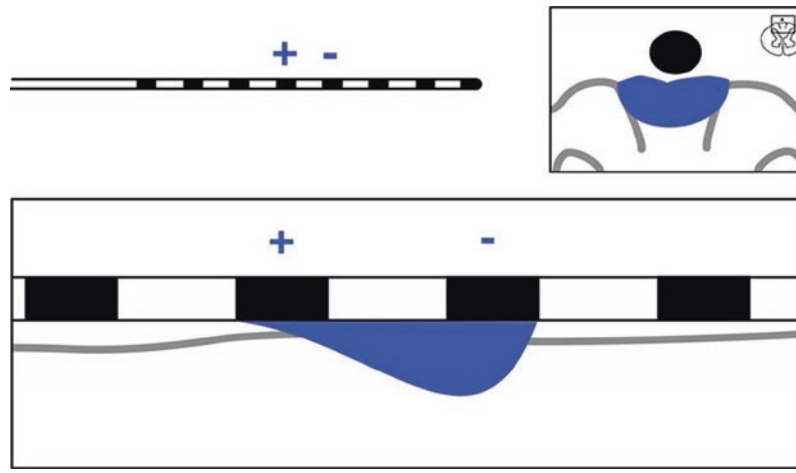

Fig. 22.2 Single anode and cathode configuration

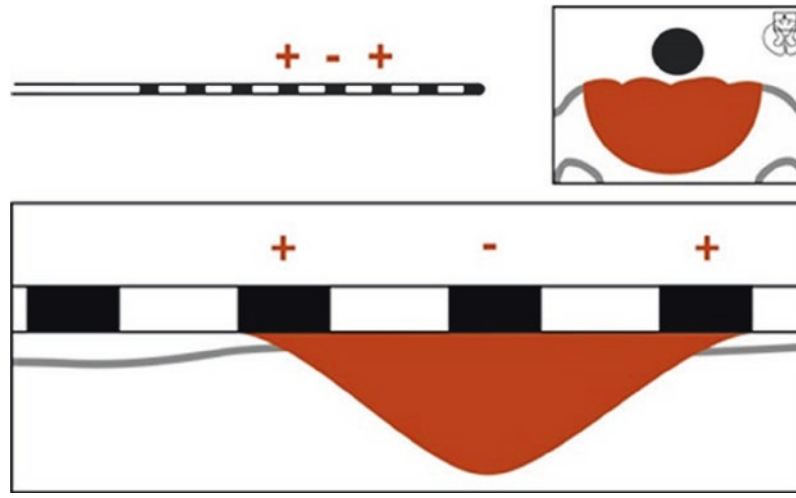

Fig. 22.3 Guarded cathode configuration

paresthesia. In the above example, the clinical usefulness of driving charge deeper into the spinal cord may be the difference between successfully capturing the desired paresthesia level and an unsuccessful trial.

Technical Aspects of Lead Placement

Preplacement Planning

Spinal cord stimulation can be utilized at all spinal levels and as such requires some preplacement planning. For example, cervical leads can be placed at the cervico-thoracic junction or via a lumbar access site with the lead maneuvered through the epidural space to the cervical target. Both approaches have merit but different applications. If one is conducting a temporary trial, then the "work" of threading leading leads from the lumbar spine for a patient who may not derive benefit may be futile [9]. Conversely, if the leads are for a permanent implant, the lumbar placement negates the need for lead extensions or extensive subcutaneous tunneling. Similarly, if leads are to be placed in the sacral space, a decision must be made whether to attempt placement in a retrograde fashion or via the sacral hiatus.

While there is wide variability among individual patients, there are some guidelines with regard to lead placement targets which may assist the clinician in preplacement planning. For instance, it is widely accepted that in the cervical spine, the C2–C5 region will encompass the shoulder to the arm/hand. Likewise many have observed that obtaining paresthesia coverage for pain in the cervical axial spine is often difficult. Pain of thoracic origin can be broadly categorized as intercostal and visceral. Intercostal paresthesia can often be obtained at or just above the thoracic level of injury in a lateral position, while visceral pain (an area of emerging application for SCS) is currently not well defined and can be highly variable when obtained at all. Paresthesia coverage of pain of lumbar origin is better described. Classic teaching states that the "target zone" for most lumbar pain has an upper limit at T8 level with neurologic mapping undertaken to find the exact location between T8 and L1 that works best for a given patient. Lumbar lead placement between L2 (termination of the spinal cord) and L5 is occasionally helpful and has many features in common with nerve root stimulation since the dorsal horn terminates at the T12–L1 level with the conus medullaris (the distal portion of the spinal cord proper at the L1–2 level). Sacral targets, though technically difficult to access, typically are relatively straightforward in their preplacement assessment in that the affected painful level is typically the optimal site for lead placement.

Physiologic Versus Anatomic Positioning

Regarding "ideal" lead placement, there is considerable variability among individual patients. Many times "ideal" lead placement based on the fluoroscopic images obtained during initial placement (Fig. 22.4) results in nontherapeutic paresthesia patterns, the second image (see Fig. 22.4) being the physiologically correct placement for that particular patient. This observation has led to the description of an anatomical midline and a physiological midline or "sweet spot" (Fig. 22.5). This jargon is describing the consistent finding that ideal anatomic position of the SCS lead under imaging (anatomic midline) often requires repositioning of the lead to less aesthetically pleasing but more desirable physiologic position to obtain paresthesia coverage of the painful area (physiologic midline). This concept suggests that dorsal column fiber position is variable among individuals, even when the spinal cord is clearly midline on MRI or CT scanning. Another aspect of this physiologic mapping that must be considered is the common observation that one patient may report paresthesia into their feet at T8 while others will experience this same sensation at T10. Further, some individuals, despite meticulous repositioning, never achieve desired paresthesia coverage of the painful area.

Anatomical Conservations

Fiber location within the spinal cord, while also variable, does have some general principles that warrant discussion. Nerve fibers of more distal structures are contained in more central locations within the spinal cord. These fibers become more superficial as they near the exit point within the spinal cord. A spinal cord homunculus analogous to the homunculus at motor cortex has been described that suggests that sacral, lumbar, and

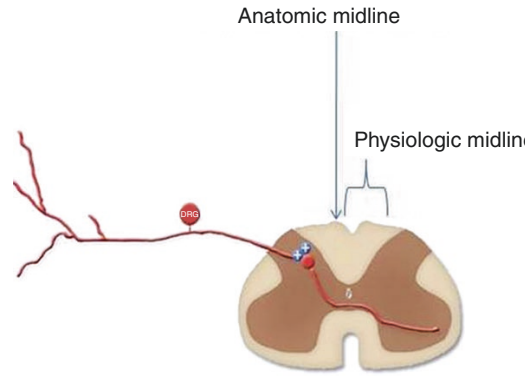

Fig. 22.5 The anatomical midline and the physiological midline or "sweet spot," terms that describe the consistent finding that ideal anatomic position of the SCS lead under imaging (anatomic midline) often requires repositioning of the lead to less aesthetically pleasing but more desirable physiologic position to obtain paresthesia coverage of the painful area (physiologic midline)

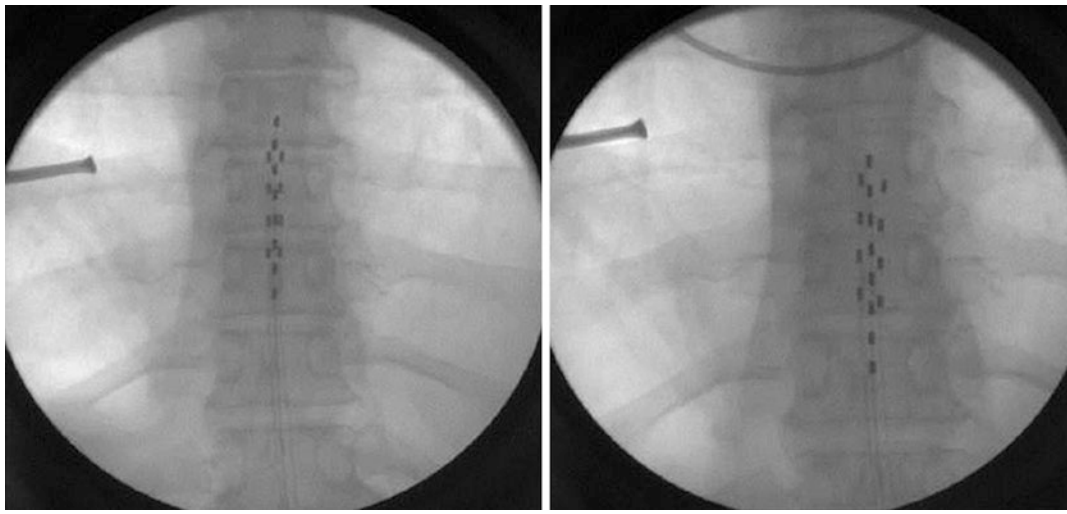

Fig. 22.4 Fluoroscopic image obtained during initial placement (*left panel*) of the "ideal" lead placement and the physiologically correct placement for this particular patient (*right panel*)

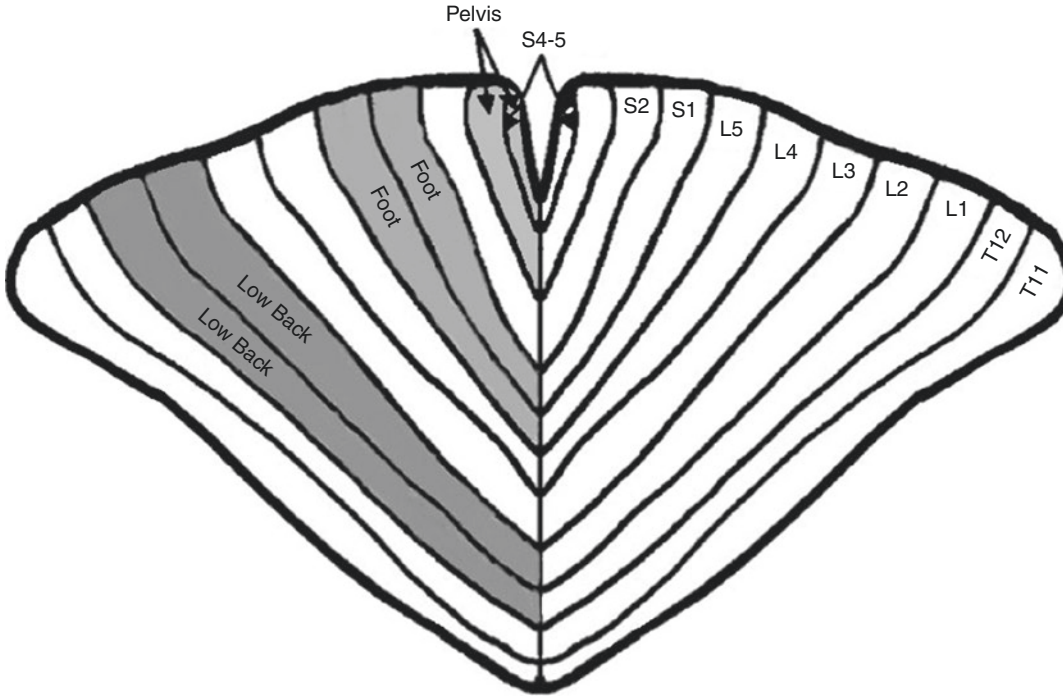

Fig. 22.6 Nerve fibers of more distal structures are contained in more central locations within the spinal cord. These fibers become more superficial as they near the exit point within the spinal cord. A spinal cord homunculus analogous to the homunculus at motor cortex has been described that suggests that sacral, lumbar, and thoracic fibers occupy fixed positions within the spinal cord ranging from medial to lateral, respectively

thoracic fibers occupy fixed positions within the spinal cord ranging from medial to lateral, respectively (Fig. 22.6). While this concept is widely taught, paresthesia mapping during trialing suggests that the concept of fiber position is of little practical value as the important lead position is the one that has practical clinical value to the patient. Also, it has been reported that nociceptors that innervate the axial spine are located at deeper levels within the spinal cord and as such require complex combinations of pulse width and amplitude to achieve penetration to these fibers [10]. With newer spinal cord stimulation modalities such as stimulation at 10,000 Hz or Burst stimulation, the anatomic position of the leads becomes more prescribed [11]. For instance, with newer waveforms, paresthesia mapping is less important; however placement in anatomic zones becomes key. For high frequency stimulation, the placement of leads in the midline in a linear array across the thoracic 9th and 10th disc interspace is prescribed as best practice. Though less prescriptive, burst spinal cord stimulation seems to have an anatomic "sweet spot" from T8 to T9 in the anatomic midline.

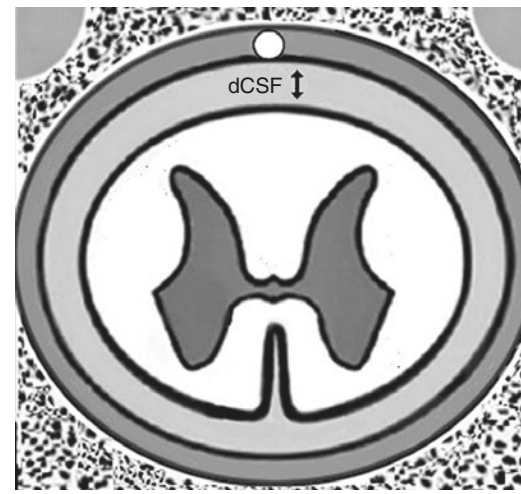

Fig. 22.7 The CSF thickness varies along the spinal column and can significantly impact stimulation

Distance between the dura and the spinal cord significantly impacts SCS. The dural cerebrospinal fluid volume varies widely along the length of the spinal cord (Fig. 22.7) and influences the dispersion of current. The CSF levels are maximal at

the T5–7 level, which fortunately from a clinical standpoint decrease in the common target zones of C4–6 and T8–L1. The CSF volume at T8–L1 is still significant enough to impact stimulation.

Technical Considerations and Trialing Techniques

Technical Considerations

The number of contacts and leads to be utilized in SCS treatment is a matter of much conjecture and little conclusive evidence. In the mid-2000s, a single or dual four-contact lead system was the state of the art. A study conducted during this period suggested that there was little advantage in adding a second lead for either radicular lower extremity or low back pain [12]. In this study, the dual lead system was associated with faster implantable pulse generator (IPG) discharge, without significant improvement in perceived pain relief. Technological advances in IPG battery life coupled with more sophisticated programming options have led to rapid adoption of eight-contact leads which when used in an 8 × 2 array result in all channels of the IPG occupied and available to be utilized [13]. A 16-contact lead has recently entered the market and is already undergoing clinical testing using a 16 × 2 array for enhanced coverage and reducing the need for lead adjustment due to lead migration. The enhanced coverage would only necessitate reprogramming as opposed to additional surgeries.

Leads configured in multiple combinations such as two leads (bipole) and three leads (tripole) have been suggested to enhance coverage of low back pain. This concept is currently under investigation. The introduction of the tripole concept allows the clinician to mimic lead contact coverage obtained with a surgical plate or "paddle" lead [14]. The broad "paddle" lead has wider contact spacing allowing coverage of a wider area within the spinal cord. There also seems to be less lead migration with the paddle lead.

Another advantage over the percutaneous lead lies in the shape of the lead itself. The cylindrical percutaneous lead "radiates" an electrical field in a 360° direction, while the surgical paddle lead directs current toward the spinal cord. It has been proposed that this arrangement directs current "deeper" into the spinal cord and may allow better axial back pain coverage. With the multiple contact percutaneous lead, the greater contact capability (8 × 1) does allow the clinician to potentially retain paresthesia coverage even if small degrees of lead migration occur [15]. It remains to be seen if the increased number of contact points is of significant benefit from a clinical perspective.

Interleaving

The programming capabilities of multiple contact points allow the programmer to utilize an advanced concept known as *interleaving* to cover multiple areas of pain. The fundamental basis of this approach utilizes the programming of the IPG to rapidly (in microseconds) switch back and forth between programs on separate portions of the lead that cover different areas of pain. For example, in an 8 × 2 configuration, lead contact 0–4 on a left-sided lead may cover low back pain, while 11–15 on the right may cover the radicular lower extremity pain. With rapid cycling between the two areas of lead contact, the patient perceives coverage of both areas. The interested reader is directed to several excellent manuscripts on this topic.

Constant Voltage Versus Constant Current

As discussed previously, all SCS systems are bound by Ohm's law in the way that they transduce the electrical signal to the biological system. If resistance (impedance in these alternating current systems) is relatively constant, and this is dependent upon the biological milieu, the only variables that can be manipulated are voltage and current. The advantages of both approaches can be theoretically debated with excellent arguments emerging for both types of systems. One study has compared constant voltage and constant current in a randomized trial, allowing the patient to

determine whether there was a preference between constant voltage and constant current systems. In this small preliminary study, patients could not reproducibly identify constant current systems from constant voltage systems, suggesting that the theoretical differences may not translate into clinically meaningful differences in therapy [16]. This fascinating topic deserves further research.

Spinal Cord Stimulation Trial Techniques

After careful preplacement planning has been accomplished, it is necessary to plan the trailing process. It is recommended that all patient candidates for SCS should undergo a pretrial psychological assessment to determine if there are unrealistic expectations, secondary gain issues, psychological issues that have not been maximally explored and treated, or other biopsychosocial factors that may impact treatment success. Once this has been done, it is necessary to discuss with the patient the trialing technique. The purpose of the trial is to temporarily allow the patient to experience the sensation of SCS without having to endure the full implantation process with the IPG. There are two types of percutaneous spinal cord stimulator trials: (1) temporary percutaneous and (2) staged percutaneous placement with permanent anchoring of the leads. Each trialing method has advantages and disadvantages. The more common temporary percutaneous method entails securing the trialed lead to the skin with suture or other easily reversible material in a fashion that is quickly and simply removed. The percutaneous placement with permanent anchoring method requires surgical incision after lead placement and anchoring identical to that which is done with permanent implantation. The anchored leads are then connected to disposable trial connectors and exteriorized via tunneling in an operative setting.

The advantages of the more common temporary percutaneous placement in comparison to permanent anchoring method are (1) easy placement and removal, (2) can be done in office procedure setting (whereas the surgical anchoring requires a traditional operating suite), (3) less post-procedure discomfort to distract the patient from the trial process, and (4) less invasive. Conversely, the percutaneous placement with permanent anchoring results in a more accurate trial to implant experience and less surgical time required for implantation of the IPG [17]. Additionally, the IPG placement can be performed under deeper sedation/general anesthesia since sensory mapping is not necessary. Occasionally, the results of the temporary trial are superior to the actual implant using the former method resulting in significant patient dissatisfaction. In the pretrial planning process, if it is suspected that spinal epidural access or lead manipulation will be difficult, it may be reasonable to do the staged trial with permanent anchoring; otherwise, most centers utilized the temporary percutaneous method.

Regardless of trialing method, it is imperative that adequate time with the therapy be given to the patient to determine efficacy. Balancing the need for time with the therapy with the risk of infection usually results in 3–5-day trial period although some clinicians advocate for at least 7 days [18]. Experience with infection rates of epidural catheters suggests that any trial up to 7–10 represents low risk from an infection standpoint. During the trial, evaluation of functional capacity, sleep hygiene, and pain reduction is key. The person who does not derive functional benefit but claims pain relief should be evaluated closely.

High-Frequency Spinal Cord Stimulation and High-Frequency Burst Stimulation

For decades traditional SCS settings have dominated the market; however, over the last 8 years, there has been promising data emerging from the increasing use of high-frequency (10 kHz) spinal cord stimulation devices (HF10) burst stimulation. These devices have similar clinical indications as the traditional SCSs and have been approved by the US Food and Drug Administration for the treatment of both back and leg pain. They operate based on the same positional and electrical current

delivery models as the traditional devices. However, contrary to the frequencies used for traditional SCS (40–120 Hz), these newer devices create currents with frequencies of 10 kHz or use burst impulses of five separated at 40 Hz with internal burst frequencies of 500 Hz or greater. While the frequencies of these devices are increased, the amplitude of the current itself is markedly decreased to levels such that they don't elicit a motor or sensory response. Therefore, in contrast to the previously described devices so highly reliant on paresthesia development to determine both proper placement and efficacy, high-frequency devices at appropriate settings do not require what can be unformatable paresthesias to generate a response.

While these devices are still in their infancy, the data are promising. A 2-year multicenter randomized control trial which included nearly two hundred patients demonstrated long-term superiority of HF10 therapy when compared to the use of traditional SCS [19]. The study examined 198 patients with chronic leg and back pain randomized into HF10 therapy or traditional SCS treatment groups and used primary and secondary end points of 3-, 12-, and 24-month intervals with respect to pain relief. What was found is that at each temporal interval, the patients demonstrated both non-inferiority and superiority of pain relief in the HF10 population [19].

In response to the significant clinical benefit of these devices, researchers have begun to explore and postulate regarding their mechanism of action. The Gate Control Theory which lead to the development of the initial SCS treatment devices does not hold water with regard to HF10 devices. The pillar of traditional paresthesia-based SCS devices is the activation of the dorsal columns and gracile nucleus to alter the interpretation pathways of pain [20]. Multiple animal studies and computer modeling have shown that HF10 therapy does not activate or even change the conduction properties of the dorsal column fibers, the gracile nucleus, or even simple peripheral mechanical stimulation responses [19, 20]. The response to the device itself is described vastly different: HF10 treatment requires hours to days to develop maximum pain relief, whereas SCS relief is apparent nearly immediately. Tiede et al. performed a multicenter prospective trial of HF10 therapy on patients who had previously tried and failed traditional SCS therapy and found 88% of the patients responded to the HF10 treatment [20]. This study further alludes to a unique mechanism of action of the HF10 treatments given its marked ability to induce relief in patients who were otherwise nonresponders to treatment.

There are multiple "working hypothesis" undergoing investigation currently as to how HF10 therapy mitigates these pain pathways: depolarization blockade, membrane integration, desynchronization, and glial-neuronal interaction [20]. The depolarization blockade theory suggests that an electrical field is created similar to the tradition model such that the neurons are further depolarized but in a local revisable manner. The membrane integration hypothesizes that the summation of the pulsatile signals creates an action potential whereas the single pulses alone would not induce a response. Both the depolarization and the membrane integration theories which mandate an altered neuronal stimulation response have data to contradict the theories. The desynchronization theory describes complex neuronal networks firing in synchrony to communicate pain and HF10's ability to desynchronize these firings. Finally, although the published data are lacking, the glial-neuronal theory describes a reformed activation of the astrocytes and microglia cells to alter the somatosensory pathways of pain [20].

Clinical Indications

While SCS has been utilized for a variety of painful axial and neurological conditions, the main indications for the therapy are as follows:

1. Failed back surgery syndrome: It has been shown that SCS has better outcomes than reoperation. These findings suggest that a trial of SCS before considering a second back surgery should be a part of the treatment algorithm.

2. Radicular pain: Pain of radicular nature in a classic dermatomal distribution in either the cervical, thoracic, or lumbar spine has a relatively strong evidence base suggesting efficacy.
3. Neuropathic pain: Perhaps the strongest indication is the intense pain of neuropathic origin. Entities such as complex regional pain syndrome types 1 and 2, post-herpetic neuralgia, and post-amputation limb pain all respond well to SCS. Of these indications, CRPS has strong clinical data to suggest efficacy.
4. Peripheral vascular disease: Such as Raynaud's phenomena, nonoperative limb ischemia, chronic angina, and Berger's disease.

While these clinical scenarios are well established as responding to SCS, there are several exciting areas of emerging application for spinal cord stimulation. Many of these applications have evidence from the case report level to suggest they may improve pain control in patient who has exhausted other possibilities. These off-label applications include:

1. Visceral/abdominal pain: There are case studies to suggest that neuromodulation can successfully be used to improve analgesia for pancreatitis and other pain of visceral origin.
2. Peripheral neuralgia: Spinal cord stimulation technology has been successfully used to treat peripheral nerve pain such as ilioinguinal/iliohypogastric neuralgia and occipital neuralgia.
3. Peripheral field nerve stimulation (PFNS): While still in the emerging stages, there is evidence of improvement with pain of myofascial and other origins that is resistant to treatment with subcutaneously placed electrodes. There have been studies published that discuss a cross-talk between the epidural and peripherally placed electrodes providing a synergistic effect for resistant peripheral pain syndromes.

Of these applications, peripheral nerve stimulation has strong data to suggest its efficacy, while visceral/abdominal applications and PFNS are still in the early stages of description.

Complications

Complications from SCS include the discomfort from implantable pulse generator (IPG), lead migration, fracture or malfunction, malfunctioning of the IPG, infection, dehiscence of wound, formation of seroma, or unwelcomed paresthesia or dysesthesias 20 [21]. A 2015 single university hospital retrospective, observational study (n = 234) saw an all complication rate of 34.6% from SCS, the majority being hardware related (Table 22.1) [20, 21]. The study saw that SCS revision and explant rate were both 23.9% (Table 22.2) [21]. An overview of complications, diagnoses, and resultant therapies is seen in Table 22.3 [22].

Table 22.1 Complications summary

	N	Complication rate (%)
All complications	81	34.6
Hardware	60	25.6
IPG discomfort or migration	26	11.1
Lead migration	20	8.5
Lead malfunction or fracture	10	4.3
IPG malfunction	4	1.7
Biologic	21	9.0
Infection	10	4.3
Unwanted paresthesia or dysesthesia	6	2.6
Dehiscence or seroma of wound	5	2.1

Adapted from Hayek et al. [21]
IPG Implantable pulse generator

Table 22.2 Revisions and explants causes

	Revisions	Explants
IPG migration or discomfort	18	8
Migration of lead	18	2
Lead malfunction or fracture	7	2
Malfunction of IPG	2	2
Infection	0	10
Required MRI	0	4
Paresthesia or dysesthesia	0	6
Dehiscence of seroma of wound	2	1
Requested by patient	0	1
Surgery requirement	0	1
Therapeutic effect that has been lost	9	23

Adapted from Hayek et al. [21]

Table 22.3 Overview of complications, resultant diagnosis, and available treatments

Symptomatic diagnosis	Complication	Treatment
Complications within neuraxis		
CT or MRI, electromyogram/nerve conduction study (emg/ncs), physical exam	Nerve injury	Steroid protocol, anticonvulsants, neurosurgery
Increased stimulation amplitude	Epidural fibrosis	Lead programming, lead revision
Physical exam, CT, or MRI	Epidural hematoma	Surgical evacuation, steroid protocol
Physical exam, CT or MRI, CBC, blood work	Epidural abscess	Surgical evacuation, IV antibiotics, ID consult
Positional headache, blurred vision, nausea	Post-dural puncture headache	IV fluids, rest, blood patch
Complications outside neuraxis		
Serosanguineous fluid in pocket	Seroma	Aspiration, if no response surgical drainage
Blood in pocket	Hematoma	Pressure and aspiration, surgical revision
Pain on palpation	Pain at generator	Lidoderm patches, injection, revision
Fever, rubor, drainage	Wound infection	Antibiotics, incision and drainage, removal
Device-related complications		
Lack of stimulation in area of pain	Unacceptable programming	Reprogramming of device, revision of leads
Inability to program, X-rays	Lead migration	Reprogramming, surgical revision
High impedance, pain at leak site	Current leak	Revision of connectors, generator, or leads
Inability to read device	Generator failure	Replacement of generator

Adapted from Deer et al. [22]

Table 22.4 Lead migration rates for SCS

Publication	*N*	Migration rate (%)	Publication type
Cameron 2004	2753	13.2	Review article
Turner 2004	830	23.1	Systematic review
North 2005	45	9	RCT
Taylor 2005	112	27	Systematic review
Kumar 2006	410	21.4	Retrospective analysis
Kumar 2008	42	14	RCT
Mekhail 2011	527	22.6	Retrospective analysis
Gazelka 2014	143	2.1	Restrospective review
De Vos 2014	40	2.5	RCT
Total	4968	Range 2.1–27	
		Mean 15.49	
		95 CI 9.21–21.77	

Adapted from Eldabe et al. [23]
RCT Randomized control trial

The most common hardware complication of SCS is lead migration. A 2015 literature review that analyzed the complications of SCS found that lead migration occurred at a mean rate of 15.49% (95% CI 9.21–21.77%) (Table 22.4) [23]. Lead migration can cause therapeutic paresthesia coverage loss; however IPG reprogramming may be all that is required to reestablish therapy. Unfortunately, most lead migrations are significant enough to warrant SCS lead revision. Factors that increase the risk of lead migration include the placement of percutaneous cylindrical leads (versus surgical paddle lead placement) and placement of leads in areas of the spine that is highly mobile, e.g., cervical spine. Other hardware complications in SCS include lead fracture and malfunction (6.37%; 95% CI 2.63–10.10%). Premature IPG battery failure is a rare hardware complication [23].

Pain related to an implanted SCS is a biological complication that has a reported mean incidence of 6.15% (95% CI 0.97–11.33%) (Table 22.5) [23]. Patients may localize pain at the IPG or lead anchor sites or at the lead extension points [23].

Wound infection is a major biological complication of SCS. The 2015 literature review reported a mean wound infection rate of 4.89% (95% CI 3.38–6.39) (Table 22.6) [23]. The review found that the generator pocket was the site for 54% of the infections, while the SCS lead made up 17%, skin incision site 8%. Infection occurred in multiple sites 14% of the time. Methicillin-sensitive *Staphylococcus aureus* encompasses the majority of these infections, with *Pseudomonas aerugi-*

Table 22.5 Rates of implant-related pain for SCS

Publication	*N*	Pain over implant (%)	Publication type
Cameron 2004	2753	0.9	Review article
Turner 2004	830	5.8	Systematic review
Kumar 2006	410	1.2	Retrospective analysis
Kumar 2008	42	12	RCT
Mekhail 2011	707	12	Retrospective analysis
de Vos 2014	40	5	RCT
Total	4782	Range 0.9–12	
		Mean 6.15	
		95 CI 0.97–11.33	

Adapted from Eldabe et al. [23]

Table 22.6 Rate of infection for SCS

Publication	*N*	Infection (%)	Publication type
Cameron 2004	2972	3.4	Review article
Follett 2004	114	N/A	Retrospective review
Turner 2004	830	4.6	Systematic review
North 2005	45	6	RCT
Taylor 2005	112	6	Systematic review
Taylor 2006	66	4	Systematic review
Kumar 2006	410	3.4	Retrospective analysis
Kumar 2008	42	10	RCT
Mekhail 2011	527	4.5	Retrospective analysis
De Vos 2014	40	2.5	RCT
Slagen 2014	22	4.5	RCT
Total	5180	Range 2.5–10	
		Mean 4.89	
		95 CI 3.38–6.39	

Adapted from Eldabe et al. [23]
RCT Randomized control trial

nosa, *Staphylococcus epidermidis*, and methicillin-resistant *Staphylococcus aureus* occurring in lower frequency [21, 24]. It has been shown that smoking and obesity, i.e., having a body mass index of ≥30, were significant risk factors in developing SCS infections and were associated in 50% and 40% of patients, respectively [21]. Factors known to impede wound healing (e.g., obesity, smoking, diabetes, malnutrition, corticosteroid use, poor hygiene) should be assessed and discussed with the patient prior implanting a SCS [21, 23]. Techniques to prevent infection include preoperative *Staphylococcus aureus* screening, intranasal mupirocin ointment treatment for positive cultures, prophylactic antibiotics administration, strict adherence to sterile techniques, and wound hemostasis [21, 24]. Complete removal of the device and intravenous antibiotic treatment is often the treatment; however SCS implant revisions impart a significantly higher infection rate when compared to the initial operation (12.5% vs 1.3%; $p = 0.02$) [21, 23].

Iatrogenic dural puncture is a rare biological complication of SCS with reported incidence of 0–0.3% [23]. Headaches and CSF leaks can occur following dural puncture. Female, age (31–50 years old), prior history of dural puncture headaches, and perpendicular (rather than parallel) orientation of the bevel have been associated with the increased risk of dural puncture. Post-dural puncture headaches may be positional and may also be accompanied by neck pain, photophobia, diplopia, and tinnitus. The resultant CSF leak may collect at the site of lead anchoring, leading to discomfort at that area or lead migration. Activities of daily living may be hampered if symptoms from dural puncture is severe [23]. If initial conservative management, i.e., bed rest, does not resolve the symptoms, an epidural blood patch can be attempted [25]. If CSF leaks persists despite mentioned therapies, surgical exploration and closure is the definitive treatment [25, 26].

Neurological injury is the worst biological complication of SCS [23]. Immediate neurological insult can be caused by direct trauma secondary to needle puncture or lead placement done percutaneously or during surgery. Delayed neurological damage can result from nerve compression from either hematoma or abscess formation [23]. Although the rate of neurological injury continues to be maintained at a low rate, it is important to recognize any neurological deficits following a SCS implant so that emergent treatment can be instituted prior to irreversible neurological damage [21, 27].

Perhaps one of the greatest unknowns is why traditional SCS has a loss of efficacy over time. Hayek et al. reported 13.7% of their patients having loss of efficacy, and 39% had had their SCS

explanted (median time 19.62 months, 95% CI 18.02–33.27) and 16.1% had revisions [21]. These changes may be due to the result of cellular changes in tissue around the electrodes, such as buildup around the contacts, or temporary changes in the electrode positioning such as lead migration or postural changes. There are many reports in the literature of painful stimulation, ineffective stimulation, or loss of stimulation over time. However, high frequency SCS treatment has not demonstrated this same pattern of decline in response over time. As the technologies are advancing, we are seeing both a reduction in complications and enhanced efficacy of stimulation.

Rare Adverse Effects

Some rare adverse effects of spinal cord stimulation are a direct result of lead placement in the spinal column. Leads placed with the goal of stimulating the caudal segment of the spinal cord can cause micturition inhibition. This unexpected development of neurologic bladder and micturition dysfunction results simultaneously with the onset of pain relief, after the beginning of an electrical stimulation of the caudal segment of the spinal cord (T11–L1) [28]. The interruption of stimulation resolves the symptoms.

Gastrointestinal symptoms are the broadest category of rare adverse side effects. The symptoms range from severe nausea caused by the spinal cord stimulator to abdominal pain and constipation [28]. Constipation and distention are directly related to above paresthesia perceptual threshold. These symptoms often resolve after several weeks and are thought to be related to GI parasympathetic tone or antidromic activation of sensory afferents.

Scar tissue formation is another issue that results in adverse effects. One such issue is cervical cord compression due to delayed scarring around epidural electrodes used in spinal cord stimulation. In a study by Dam-Hieu et al., two surgeries were required to correct this issue [29]. The removal of the SCS alone was not effective. However, the removal of the scar tissue resulted in significant improvement of symptoms. Another similar complication is late-onset cervical myelopathy secondary to fibrous scar tissue formation around the spinal cord stimulation electrode [30]. A similar case was also reported as spinal cord compression from a foreign-body reaction to spinal cord stimulation [31]. An epidural mass causing significant cervical stenosis and spinal cord compression occurred in one case at the site of a previous SCS. Decompressive laminectomies and a resection of the mass were required.

It is important to understand that these are rare, isolated cases of SCS causing adverse effects. The aforementioned adverse effects are possible in an SCS implant and therefore must be monitored.

Evolving Technologies and the Future of SCS

Spinal cord stimulation originally consisted of monopolar leads connected to external generators to create the electric field around the spinal cord for the treatment of chronic pain. Since then we have expanded to fully implanted rechargeable batteries and leads have progressed from monopolar plates to multiple leads with multiple contacts allowing for up to 32 contacts. More impressive is that each contact has individual power sources to maximize precision targeting of pain. In addition to the continual improvements in technology, the field of SCS has expanded from stimulating only the spinal cord to also being applied to regions of the brain, now called deep brain stimulation (DBS), as well as peripheral nerve stimulation being applied to more peripheral structures like the dorsal root ganglia.

The paresthesia-free analgesia induced by high-frequency SCS therapy continues to yield strong clinical results. While the fundamental mechanism for SCS remains elusive, the unrefutable results of the therapy illuminate what could be a new and effective tool to help those suffering from chronic pain. Similarly, as we remain in the exploratory stages of therapies, recent data show that the definition of high frequency may change in the coming years. Multiple investigations have compared paresthesia-free SCS therapies at fre-

quencies of just 1 kHz to the effectiveness of traditional SCS therapy and have found improved analgesia responses [20]. These studies demonstrate that 10 kHz therapy may not be required to disrupt these pain pathways, and similar analgesia may be induced at much lower frequencies. More research is required as to define the optimal frequency and delivery mode which may potentially allow us to better titrate current therapy.

Similarly as we better illuminate the complexities of the neuronal and biological pain matrix, the proposition of "drug-enhanced spinal stimulation" therapy becomes a viable opportunity to further specify and personalize treatment strategies. It was demonstrated in animal studies that the SCS-induced analgesia was reversed by adding a GABA antagonist demonstrating the significance of GABA on SCS-mediated analgesia [22]. In response, a recent study performed on rats deemed "nonresponders" to SCS showed that following intrathecal GABA-B agonist treatment with Baclofen, a large majority of the subjects were transformed into responders [29]. Other studies investigating serotonin have shown that the effect of SCS at subthreshold was made effective upon administration of typically non-analgesic doses of serotonin linking SCS to the serotonin pathway. Additional studies have shown that serotonin and substance P are released following SCS. A more complete list demonstrating the efficacy of SCS with cotreatment of various neurotransmitters is summarized in Table 22.7 [24]. This data provides a potential field of neurobiological supplementation therapy as an adjunct to further enhance SCS treatment in the appropriate patient.

Table 22.7 Effect of various spinal originating transmitters on efficacy of SCS

Spinal neurotransmitter	Effect of cotreatment with SCS
Acetylcholine	Increased
Adenosine	Increased
GABA	Increased
Norepinephrine	Increased
Serotonin	Increased
Substance-P	Increased
Aspartate	Decreased
Glutamate	Decreased

Adapted from Wada and Kawai [32]

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New Vistas: Intraoperative Neurophysiological Monitoring and Small-Pain-Fibers Method of Testing for Spinal Cord Assessment in Pain States

Alan David Kaye, Amit Prabhakar, Matthew B. Novitch, Jordan S. Renschler, and Elyse M. Cornett

Introduction

The number one overall complaint from patients in an outpatient clinical setting is pain. At times, the diagnosis and treatment of a given pain syndrome can be challenging. Patients present to pain clinics for a multitude of different reasons. In any physical examination involving a chronic pain patient, a thorough sensory neurological examination is important. Clinicians need to understand the evolution of nerve testing and to be able to differentiate the small-pain-fibers method of testing from previous techniques. In the 1940s, a logical approach to the sensory examination was identified with defined surface areas highly correlated with specific anatomic dermatomes. These dermatomes are associated with specific nerve roots and are very useful for the clinician attempting to ascertain the source of a pain generator. The concept of current perception threshold was later developed to measure the level of sensory deficit. There was significant variability associated with this diagnostic technique, which involved changing skin resistance. These limitations led to further evolution and development of sensory conduction testing which will be discussed in this chapter.

Sensory Nerve Conduction Threshold Testing

A sensory nerve conduction threshold test (sNCT) is a psychophysical assessment of both central and peripheral nerve functions. It measures the detection threshold of specifically calibrated sensory stimuli. Normal sensory nerve action potentials indicate that the cells of the dor-

A. D. Kaye (✉)
Departments of Anesthesiology and Pharmacology, Toxicology, and Neurosciences, LSU School of Medicine, Shreveport, LA, USA

LSU School of Medicine, Department of Anesthesiology, New Orleans, LA, USA

Tulane School of Medicine, New Orleans, LA, USA

A. Prabhakar
Emory University School of Medicine, Department of Anesthesiology, Division of Critical Care, Atlanta, GA, USA

M. B. Novitch
University of Washington, Department of Anesthesiology, Seattle, WA, USA

J. S. Renschler
Louisiana State University School of Medicine, Departments of Anesthesiology and Pharmacology, New Orleans, LA, USA

E. M. Cornett
LSU Health Shreveport, Department of Anesthesiology, Shreveport, LA, USA

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sal root ganglion and the large myelinated axons are healthy and intact. If a patient has numbness, the abnormal process lies proximal to the dorsal root ganglion, or the patient has common small fiber or nociceptive neuropathy. Sensory nerve conduction testing can localize the anatomic basis of the disease and may become abnormal earlier in the course of a disease state as compared with motor nerve conduction testing. This procedure is intended to evaluate and quantify function in both large- and small-caliber fibers for the purpose of detecting neurologic disease. Sensory perception and threshold detection are dependent on the integrity of both the peripheral sensory apparatus and peripheral-central sensory pathways. In theory, an abnormality detected by this procedure may signal dysfunction anywhere in the sensory pathway including the receptors, the sensory tracts, and the primary sensory cortex up to the association cortex. This procedure is distinct from an assessment of nerve conduction velocity, amplitude, and latency. It is also different from short-latency somatosensory-evoked potentials. This instrument provides testing which is voltage mediated, and results are independent of changes in skin resistance. Essentially, voltage-actuated sensory nerve conduction has resulted in the development of a different type of instrument to quantitate sensory function.

Sensory nerve conduction studies are performed by electrical stimulation of a peripheral nerve and are recorded from a purely sensory portion of the nerve, and the recording electrode is the more proximal of the two. Sensory latencies are on the scale of milliseconds. Sensory amplitudes are much smaller than the motor amplitudes, usually in the microvolt (μV) range. The sensory nerve conduction velocity is calculated based upon the latency and the distance between the stimulating and recording electrode.

Sensory nerve conduction information can lead to a diagnosis other than peripheral neuropathy to explain the process that is occurring. It is limited in that it is not precise as to the site of deficit. sNCT testing is applicable and useful in many different clinical environments but may particularly be useful in the realm of spinal cord stimulation. The sNCT test measures painless current perception thresholds (CPTs) and atraumatic pain tolerance thresholds (PTTs). Spinal cord stimulation modulates segmental large afferent fiber input, and sNCT testing reflects increases in both large and small fiber CPTs when functioning correctly. Monitoring spinal cord stimulator functionality via this method can confirm a sensory (suprasegmental) modulating effect on nociceptive fiber activity.

Additionally, despite the widespread application of sNCT testing and possible aid in assessing neuropathy, in 2004 the Center for Medicaid Services concluded the use of any type of sNCT device to diagnose sensory neuropathies or radiculopathies in Medicare beneficiaries is not reasonable and necessary. This has created a need to have more precise and cost-effective methods to define the specific pathological etiology.

The Small-Pain-Fibers Method

In 1998, the small-pain-fibers method was approved by the FDA. The pain-fiber nerve conduction threshold (pf-NCT) method uses an electrical stimulus with a neuroselective frequency to determine the minimum voltage causing conduction. Rather than comparing the data with population averages on a bell-shaped curve which has about 65% sensitivity, the patient is his control (e.g., a nerve on the left hand is measured against a nerve on the right hand). In a 3-year Louisiana State University School of Medicine Pain Center study, it was found that the nerve requiring the greatest voltage to cause conduction of the A-delta (fast pain) fibers identified nerve root pathology with 95% sensitivity. The test is painless and rapidly performed. A new version uses a potentiometer to objectively measure the amplitude of the action potential applied at a distant site along the nerve being tested. The previous version required the reporting of a sensation when the nerve fired, which introduces potentially confounding variables. This test does not require the patient to report a sensation though one may be experienced nor does it require myelin loss to detect function change (such as nerve conduction velocity testing), so velocity is not measured.

Devices used for pf-NCT such as the PAIN-NCS and Axon-II consist of a potentiometer (detector) placed near the spine, a ground sponge placed on the back, and a test probe (stimulator) placed near peripheral nerves being tested. An electrical stimulus of set frequency is applied with increasing amplitude until the potentiometer detects electrical nerve conduction. One such device that uses this technology is the neural scan. The neural scan has been shown to be an effective diagnostic device designed to identify selective nerve pathology by measuring the amplitude of localized sensory nerves, not only nerve functionality. A sNCT testing device only identifies a dysfunction somewhere in a sensory pathway, making the small-pain-fibers technology valuable regarding accuracy and precision of spinal cord pathology. A small-pain-fibers device assesses nerve pathology by measuring nerve response at differing points along a sensory nerve. It does not rely on the integrity of the overall central sensory pathways to the cortex rather specific and individual sensory nerves. Small-pain-fibers technology performs pain fiber nerve conduction studies by measuring the amplitude of the stimulus and the amplitude of the action potential.

In summary, the small-pain-fibers method of testing for spinal cord pathology is relatively new and largely unknown in the medical community. Future studies are warranted to better understand this technology and its role in identifying spinal cord pathology.

Altered Intraepidermal Nerve Fiber Density in Suspected Small Fiber Neuropathy

Determining intraepidermal nerve fiber (IENF) density is a useful clinical tool in the diagnosis of small fiber neuropathies (SFNs). SFNs involve C-fibers and Aδ-fibers conveying nociceptive and thermal stimuli and often present clinically as a burning sensation with diffuse pain. Despite the pain of SFNs, routine examination and electrodiagnostic studies do not determine the underlying pathology and often show no abnormalities in these conditions. IENF imaging is especially useful in patients with peripheral neuropathy and normal electrodiagnostic studies. IENF density is significantly reduced in patients with SFNs.

Analysis of skin biopsies using immunohistochemistry or indirect immunofluorescence can dependably identify IENFs. In several systemic illnesses, including diseases associated with mutations in genes encoding ion channels, immune-mediated SFNs, and neurodegenerative disorders, visualization of degenerated IENFs reveals the underlying pathology of the perceived pain. SFNs are most often seen in diabetes mellitus type II but have also been implicated in other diseases and idiopathic peripheral pain. Recent studies have established reference ranges for comparison, making these imaging methods clinically useful.

Methods of Intraoperative Neurophysiological Monitoring

With the increasing number and wide variety of spinal surgeries, iatrogenic neurologic injury is a rare but increasingly real complication. To reduce perioperative neurologic deficits, intraoperative neuromonitoring techniques (IONM) have been developed with notable technologic advancements over the last four decades. There are two main methods for IONM, specifically combined somatosensory-evoked potentials (SSEPs) and motor-evoked potentials (MEPs). MEPs have been shown to have better sensitivity and specificity for new spinal cord deficits. Because of this increased accuracy, utilization of MEPs has become more commonplace in spine procedures over the last few decades relative to somatosensory-evoked potentials. Several specific newer methods of motor-evoked potential monitoring include transcranial motor-evoked potentials (tcMEPs), descending neurogenic-evoked potentials (dNEPs), and spontaneous electromyography. These newer methods utilize the same basic principles and offer alternative monitoring techniques when conventional techniques are unavailable or too difficult to employ.

In tcMEPs, the motor cortex is stimulated transcranially via electrodes placed on the scalp that act on the motor cortex with a pulse train of high-voltage, short-duration signal. Recording of peripheral muscles responses allows for testing of the entire motor pathway. This is favorable in events such as anterior spinal artery syndrome, where SSEP responses would fail to identify changes in spinal cord function because the dorsal columns would remain intact.

dNEPs record motor-evoked potentials from peripheral nerves or muscles via either direct or indirect stimulation of the spinal cord. An indirect stimulus is provided via the placement of needles into consecutive spinous processes. Direct stimulation is achieved by insertion of an epidural catheter onto the dura through a laminotomy defect within operative spinal levels. The sciatic nerve at the popliteal fossa is a common anatomical landmark for recording responses distally. dNEPs can help localize the area of spinal cord deficit by systematically stimulating at multiple points along the spinal column, allowing for precise mapping of the injury level.

Spontaneous electromyography detects the spontaneous electrical activity of muscles. Bipolar needles are used either intramuscularly or subdermally to detect neurotonic discharges from muscles during spine surgery. Proper needle placement is essential for an accurate EMG recording, with the electrodes being placed into the "belly" of each recorded muscle. Baseline EMG values are recorded before surgical start, and continuous recordings are made throughout the case. Unlike other modalities, spontaneous electromyography can provide real-time information about intrinsic nerve root function.

Historically, the ability to reliably monitor sensory afferents during cerebellopontine angle surgery has been difficult. However, in 2018 a new method utilizing the blink reflex was proposed by Simioni et al. The blink reflex can monitor the integrity of the sensory component of the trigeminal nerve, corresponding brainstem connections, and the facial nerve. More studies need to be performed, but the blink reflex has the potential to be a promising adjunct for neurophysiological monitoring in the future.

A case report from May 2018 showed how these methods of intraoperative neuromonitoring can be employed in a practical and clinically relevant manner. The case report addresses two cases of surgical correction of secondary scoliosis and describes monitoring spinal cord segments cranial and caudal to the level of an acute spinal cord injury using epidural electrodes. In both cases there was an intraoperative spinal cord injury during the instrumentation, which was detected by loss of the tcMEPs caudal to the intercostal thoracic muscles and loss of the lower limb somatosensory-evoked potentials (SSEPs). The level of spinal cord damage was identified and confirmed by combined use of spinal cord recorded SSEPs and D waves. Two epidural recording electrodes were placed, one cranial and one caudal to the level of the lesion. In both cases, the spinal cord SSEPs were absent above the lesion but present below. D waves were present above the lesion and absent below. In these cases, during the remainder of the surgery, the authors used epidural SSEPs for monitoring of spinal cord function caudal to the lesion and D wave for the levels cranial to the lesion. They also performed the spinal cord-to-spinal cord-evoked potentials (stimulating proximally and recording distally to the lesion using the epidural electrodes), demonstrating a reproducible potential, which remained stable throughout the remainder of the surgery. They concluded spinal cord monitoring using epidural electrodes in patients with acute intraoperative spinal cord lesions facilitates identification and confirmation of the level of spinal cord injury, allows the surgeon to continue with the instrumentation in those cases when necessary, and can help establish a postoperative prognosis.

In summary, this chapter describes new horizons for diagnosing neuropathies and neurophysiological monitoring. These newer methods have the potential to increase accuracy, allowing practitioners to make more informed clinical decisions and to improve patient outcomes. Clinicians should be cognizant of the different approaches for the evaluation of neurologic injuries.

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