

# Peripheral Nerve Monitoring During Operative Procedures

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#### **CME Information**

**Product: MM49 - Peripheral Nerve Monitoring During Operative Procedures**

#### **Course Description**

Monitoring of peripheral nerve function is important during the surgical treatment of peripheral nerve and plexus lesions, allowing for rapid assessment of the integrity of the roots, plexus, and nerves. The results of this monitoring assist the surgeon in the overall approach to treatment of these lesions. There are, however, many technical challenges to providing this neurophysiological information in an accurate and rapid fashion. This study assesses the equipment and techniques involved in intraoperative peripheral nerve monitoring and describes its use in the more common clinical scenarios.

#### **Intended Audience**

This course is intended for Neurologists, Physiatrists, and others who practice neuromuscular, musculoskeletal, and electrodiagnostic medicine with the intent to improve the quality of medical care to patients with muscle and nerve disorders.

#### **Learning Objectives**

Upon conclusion of this program, participants should be able to:

1. describe the uses of peripheral nerve stimulation and intraoperative monitoring during operative procedures.
2. describe techniques of peripheral nerve stimulation during surgical interoperative monitoring.
3. assess technical problems associated with the operative monitoring of peripheral nerves.

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**ABSTRACT:** Monitoring of peripheral nerve function is important during the surgical treatment of peripheral nerve and plexus lesions, allowing for rapid assessment of the integrity of the roots, plexus, and nerves. The results of this monitoring assist the surgeon in the overall approach to treatment of these lesions. There are, however, many technical challenges to providing this neurophysiological information in an accurate and rapid fashion. This study assesses the equipment and techniques involved in intraoperative peripheral nerve monitoring and describes its use in the more common clinical scenarios.

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## PERIPHERAL NERVE STIMULATION AND MONITORING DURING OPERATIVE PROCEDURES

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**E**lectrophysiological monitoring of peripheral nerves during surgery is an extremely valuable procedure that provides vital, real-time information to the surgical team. Preoperative electrophysiological testing provides the surgeon with valuable data to assist with decision-making; however, there is information that simply cannot be obtained from these studies, and intraoperative studies help bridge this gap. Monitoring of peripheral nerves during surgery has been described and studied for nearly 40 years<sup>21,22</sup> and has been the subject of several reviews<sup>14,30,31,33</sup> as well as a monograph.<sup>2</sup> Intraoperative monitoring (IOM) requires a skilled and knowledgeable team of physicians and technologists who ensure rapid and accurate acquisition and interpretation of electrophysiological data. It also requires a good working relationship with the entire surgical team. Communication with the surgeons is vital in assisting decision-making between divergent surgical plans. Accurate and timely communication with the

anesthesiologist is also important as certain anesthetic agents can have detrimental effects on electrophysiological studies. Having a peripheral nerve IOM plan prior to surgery is ideal to maximize the efficiency and utility of the studies.

The uses for peripheral nerve IOM monitoring include: (1) identifying peripheral nerves; (2) localizing pre-existing disease processes along the course of a nerve; (3) determining the functional continuity across a pre-existing lesion, prior to detection by other electrophysiological means; (4) determining likelihood of nerve root avulsion; (5) identifying targets for nerve biopsy; and (6) monitoring and thereby preventing damage to intact nerves during surgery.

This review provides background on the equipment and techniques used for intraoperative peripheral nerve and plexus monitoring and an interpretation of the findings obtained thereby. The use of nerve conduction studies (NCSs), needle electromyography (EMG), and evoked potentials (EPs) is considered. For the purpose of this review, the term “peripheral nerve” applies to nerve distal to the spinal cord, and also distal to the intervertebral foramen (spinal root/nerve, plexus, peripheral nerve). The application of these electrodiagnostic (EDX) techniques is described for specific clinical scenarios. The use of IOM involving cranial nerves has recently been reviewed and is not addressed.<sup>12</sup>

**Abbreviations:** ADM, abductor digit minimi; CMAP, compound muscle action potential; EDX, electrodiagnostic; EEG, electroencephalogram; EMG, electromyography; EP, evoked potential; IOM, intraoperative monitoring; NCS, nerve conduction study; NAP, nerve action potential; MEP, motor evoked potential; MRI, magnetic resonance imaging; MUAP, motor unit action potential; SEP, somatosensory evoked potential; SNAP, sensory nerve action potential; UNE, ulnar neuropathy at the elbow

**Key words:** brachial plexopathy; intraoperative monitoring; intraoperative nerve stimulation; motor evoked potentials; nerve root avulsion; somatosensory evoked potentials

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### TECHNIQUES

**Nerve Conduction Studies.** NCSs are performed with stimulation and recording of motor, sensory, or

mixed nerves, yielding a nerve action potential (NAP). Potentials can also be recorded over muscle [compound muscle action potentials (CMAPs)] or centrally over spine or scalp (EPs). Many factors dictate which of these (or what combination) are used, and this, in turn, dictates the type of equipment necessary and the regimen of anesthesia that should be utilized.

Intraoperative peripheral nerve stimulation is usually performed directly on the surgically exposed nerve. A bipolar stimulator is held in place by the surgeon with the cathode directed toward the recording electrodes. The interelectrode distance is usually 3 mm, although the distance is dictated by the size of the nerve. A larger nerve such as the sciatic nerve demands a larger interelectrode distance, such as 7 mm. The proper orientation of the stimulating electrodes is important, and visual confirmation of correct placement by the IOM physician or technologists in the operating room is useful. If the bipolar orientation is not possible, monopolar stimulation can be performed with the cathode on the nerve and the anode some distance away. This should generally be avoided, however, as stimulation cannot be focused precisely, and the current may spread to adjacent nerves as well as farther down the nerve being studied. Bipolar stimulation results in less current spread and is therefore preferred. Another possible technique is using a tripolar stimulating electrode.<sup>22,34</sup> In tripolar stimulation, a single cathode is situated between two anodes. This further focuses the site of stimulation while minimizing the stimulus artifact. The size of the stimulating electrodes should be in concert with the size of the nerve. Special stimulating electrodes, some with hooks or very small pointed tips, often need to be used with this technique. During stimulation, the nerve should be elevated out of the surgical field to avoid contact with excessive fluid, which effectively reduces the stimulus received by the underlying nerve. Our stimulating electrodes are made of a silver solder alloy and are gas-sterilized or autoclaved after surgical procedures.

The amount of stimulation required to depolarize the underlying axon is less than that needed for percutaneous stimulation. Excessive stimulation must be avoided in order to limit current spread down the stimulated nerve and to other nearby nerves and muscles.

Excessive stimulation also increases the stimulus artifact, which becomes a larger problem as the distance between stimulating and recording electrodes is lessened. A square-wave pulsed stimulus with a duration of 0.05 ms and intensity of only a few

milliamperes (1–5) is usually sufficient for depolarization of the axonal membrane in a supramaximal fashion. Of note, short-duration stimulation of this type is more likely to preferentially activate motor axons.<sup>36</sup> For constant-voltage stimulation, intensities of 25–50 V are used.<sup>25</sup> It is important to remember that, in diseased nerves, higher stimulus intensity may be needed to reach threshold. It is our practice to increase the stimulus intensity up to 20–25 mA if no response is obtained initially. These higher intensities, however, result in increased stimulus artifact and likely evoke volume-conducted responses rather than true NAPs (see below). Since the size of the NAP is small (microvolts), averaging one to five responses is often helpful (although when a response is present, it is usually visible after the first stimulus). When there is no visible twitch from the muscle and no elicited electrical response, it is imperative to ensure that stimulation is indeed occurring. The stimulating electrodes then are placed on a nearby known functioning nerve or muscle to assess for twitch. Even in the setting of neuromuscular blocking agents, direct stimulation of muscle should result in a twitch.

NAP recording takes place along the course of the stimulated nerve. The distance between the cathode and the active recording electrode should be at least 4 cm to minimize stimulus artifact. The interelectrode distance is 3–5 mm, with a wider separation used when there is a longer distance between the cathode and recording electrode. This allows for the longer traveling wave to pass completely under the active electrode before passing under the referential electrode. The farther the separation, however, the more likely it is that extraneous noise and stimulus artifact will differ at the two recording electrodes and will not be rejected as common mode signals by the differential amplifier. The nerve should be lifted out of the surgical field as at the site of stimulation. The recording electrodes are held in place by the surgeon and visual confirmation of the correct orientation (active electrode toward the cathode) should be obtained. The size of the recording electrodes should match the recording nerve. A three-pronged electrode with a ground–active–referential arrangement has also been used. Electrodes can be used for either stimulating or recording, depending on whether they are connected to the amplifier or stimulator. Bipolar point electrodes are generally used for stimulation and the curved hook electrodes for recording. The ground electrode is a flat metal plate that is placed under the patient and is separate from the ground used for cautery.

Since the NAP waveforms contain frequencies in the 1-kHz range, it is appropriate to use filter settings of 5–10 Hz for the low-frequency (high-pass) filter and 2–3 kHz for the high-frequency (low-pass) filter. Occasionally, it is helpful to increase the high-frequency filter to better separate the NAP waveform from stimulus artifact.<sup>34</sup> The NAP amplitude is usually less than 100  $\mu\text{V}$ , so a gain of 20–50  $\mu\text{V}$  per division is utilized. The latency will depend on the length between stimulating and recording electrodes. A simple guide is 1 ms per 5-cm distance (assuming 50-m/s conduction velocity). A time base of 0.5 ms per division is reasonable, but should be increased for longer distances.

When the goal of intraoperative peripheral nerve studies is to determine the functional continuity or the exact location of a peripheral nerve lesion, stimulation and recording will need to be performed on either side of the lesion. The orientation may vary depending on the accessibility to the nerve. When assessing for continuity, it is important to realize that the presence of only a few large myelinated axons can produce a response with a relatively normal conduction velocity, latency, and threshold; therefore, it is most useful to assess the amplitude of the NAP to determine the number of functioning axons across a lesion. A NAP proves the existence of a large number (over 4000) of functioning, medium-sized, myelinated axons.<sup>21</sup> Stimulation is usually performed proximal to the lesion, with recording distal. When localizing lesions, recording electrodes are generally placed proximally and the stimulating electrodes are moved from proximal to within, and then distal to, the suspected lesion, assessing for a change in morphology of the waveform when a step is made into or across the lesion.

Recording CMAPs has the advantage of amplification of responses as each axon innervates and activates hundreds to thousands of muscle fibers. Amplitudes are measured in millivolts, as opposed to microvolts in NAP and EP recordings. CMAP recording is performed with surface (as in routine NCSs), subcutaneous, or intramuscular electrodes. Subcutaneous recordings are performed with electroencephalographic (EEG) needles placed above or into the muscle of interest. Fine, longer, intramuscular wires placed with the use of a hollow needle can also be utilized. Both intramuscular and subcutaneous recordings limit the size of the recording area, thereby reducing extraneous noise in the recording. Intramuscular recordings record from a small part of a muscle and therefore reflect activity in a fraction of the axons that might be stimulated intraoperatively. They also tend to introduce more extraneous noise

than subcutaneous EEG electrodes and are not suitable for IOM if the amount of innervation to a muscle is important to measure. This technique is most often utilized for deep muscles or muscles that are smaller or where selective recording is difficult (e.g., rhomboids, laryngeal muscles). Subcutaneous EEG electrodes are favored at the authors' institution given the ease of placement and quiet recordings and the ability to better quantify the number of functioning axons.

**Evoked Potentials.** Responses from stimulation of peripheral nerve can also be recorded from the spinal cord and cortex as somatosensory evoked potentials (SEPs). Stimulation of peripheral nerve will depolarize both motor and sensory axons; however, selective orthodromic recording from central sensory pathways ensures that only the large-fiber/dorsal-column pathway is assessed, just as it does with percutaneous stimulation in routine SEPs. Since the goal for intraoperative SEPs (in most cases) is to assess nerve root continuity, stimulation is performed as close to the intervertebral foramen as possible. The cathode is directed proximally and recording is performed from the cervical spine level via either a nasopharyngeal electrode or from a needle electrode placed directly on the lamina in the cervical spine. Scalp EEG electrodes are placed at C3' and C4' with Fz as a reference (international 10–20 system). These responses are small in amplitude, so many stimuli must be averaged—typically 20–50 stimulating at 1.1–1.9 Hz. Stimulus intensity is typically between 10 and 20 mA. The presence of a central response (scalp or cervical spine) indicates the continuity of the dorsal root in cases where avulsion is questioned.<sup>15,26</sup> Although this does not directly test the ventral root, its separate continuity is often assumed when a response is obtained.<sup>26</sup> Lack of a response argues for dorsal nerve root avulsion or disruption, especially when NAPs can be recorded from the corresponding spinal nerve or plexus element. In a pure preganglionic lesion affecting the dorsal roots, the cell body and peripheral sensory axons are still intact and a peripheral NAP would be expected, usually with normal conduction velocity.

Motor evoked potentials (MEPs) from transcranial electrical stimulation can be recorded peripherally at the intervertebral foramen, at the same location as stimulation for SEPs. Anodal stimulation is utilized with a short-duration (0.05 ms), rapid-rise-time stimulus using subcutaneously placed EEG electrodes at C3 and C4. Single or several (2–5) stimuli with an interstimulus interval of 1 ms are given with an intensity of 200–600 V. Direct nerve recording is



performed with the bipolar electrodes described above, usually placed onto the spinal nerve as close to the exit from the intervertebral foramen as possible. A response indicates continuity of the ventral root, whereas absence of a response suggests root avulsion or nonfunctioning axons.<sup>35</sup> Neuromuscular paralysis is often employed to eliminate volume-conducted muscle artifact from neck and proximal arm muscles. Excessive stimulus artifact can also be a problem given the short distance between stimulating and recording electrodes. Occasionally, it is necessary to move the recording electrodes distally onto brachial plexus elements to obviate this artifact. The polarity of the stimulus can also be reversed and several stimuli averaged in an attempt to reduce the stimulus artifact by phase cancellation. The MEP latency is typically in the neighborhood of 8 ms when recording from the cervical roots.

MEPs can also be recorded from muscle using a surface, subcutaneous, or intramuscular electrode. The size of a response in this situation may have more to do with the distance between any depolarizing muscle fibers and the recording electrodes than with the actual number of functioning axons. Although a response does indicate continuity or reinnervation to the particular muscle, it cannot prove the continuity at individual roots: even with lack of continuity of one root (e.g., C5), a MEP could still be recorded over a muscle (e.g., biceps) due to innervation by another root (C6). Also, a MEP recorded from muscle may be due to only minimal reinnervation of a few axons that may not result in meaningful recovery. An absent MEP recorded over muscle does not disprove continuity or reinnervation across a lesion as there may be regenerating axons that have not yet reached the muscle. An absent muscle response cannot distinguish between a pre- and a post-ganglionic lesion. The most accurate ways of predicting nerve (especially root) continuity and axonal regeneration are the procedures of recording MEPs over the nerve roots and evaluating for proximal NAPs.

In both SEP and MEP recordings, it is desirable to have a "normal" control to confirm the correct functioning of all equipment and the reliability of the study. This ideally would entail study of a spinal nerve known to be functional by clinical examination, radiological studies, or preoperative electrophysiological studies, with the expectation of SEP and MEP responses. An absent response would indicate a technical problem that would need to be remedied before further testing is undertaken. Along the same lines, when there is concern regarding a false-positive response (e.g., a volume-conducted

muscle response in the MEP study), recording of a spinal nerve from a known avulsed ventral root is helpful; a response there confirms a likely false-positive response from the other root. A neuromuscular blocking agent could also be used to make this distinction. If the waveform in question disappears or decreases in size, a volume-conducted response is most likely. Given the limited surgical exposure in most cases, however, this control neurophysiological assessment can be difficult or impossible to accomplish. As an alternative, the contralateral limb can be tested by stimulation of the median nerve at the wrist, checking for SEPs over the cervical spine and scalp. A MEP can be recorded over a limb muscle [biceps or abductor digit minimi (ADM)]. The recording electrodes over the ADM can also be used to record a CMAP with peripheral (wrist) stimulation in the monitoring of neuromuscular blockade.

In choosing which technique (SEP or MEP) should be used for monitoring purposes, it is important to realize that, from a surgical reconstruction perspective, the continuity of the ventral roots is the most functionally important factor to determine. Functioning ventral roots can be used as the proximal stump for nerve grafting. The loss of the ventral roots as a grafting vehicle will necessitate other transposition procedures utilizing nerve or nerve-muscle transfers from other territories.<sup>29,31</sup> The continuity of the dorsal root does not guarantee continuity of the ventral root, and vice versa.<sup>26</sup> A mismatch (partially avulsed dorsal or ventral roots) was noted in 11% of roots studied by laminectomy.<sup>8</sup> In most of these instances, the ventral root was avulsed with an intact dorsal root. A combination of these two IOM techniques (SEP and MEP), therefore, may be ideal.<sup>3,14</sup>

**Needle Electromyography.** Monitoring needle EMG activity during surgery can give relatively noninvasive, real-time information regarding the status of motor axons. A recording electrode placed in a muscle can be used to identify abnormal activity, namely neurotonic discharges. Neurotonic discharges are high-frequency bursts of motor unit action potentials (MUAPs) either firing briefly or in more prolonged trains.<sup>9</sup> These bursts or trains are made up of MUAPs firing at 30–100 Hz. Neurotonic discharges are caused by mechanical irritation to axons, including traction, stretch, manipulation, or saline irrigation. They must be distinguished from irregular voluntary MUAPs occurring under light anesthesia or from other electrode or surgical (i.e., cautery) artifacts. Although neurotonic discharges are sensitive indicators of nerve irritation, their presence does not always indicate damage to axons and their ab-

sence does not guarantee lack of damage. Neurotonic discharges are, for example, common in some spine surgeries, although postoperative radiculopathy is rare.<sup>11</sup> It is important to note that sharp transection of a nerve may produce no neurotonic discharges. Neurotonic discharges are less likely to be produced after mechanical stimulation in previously damaged nerves. Neurotonic discharges can still be recorded with neuromuscular blocking agents producing up to 75% block, as measured by CMAP amplitude.<sup>16</sup>

Free-running recording can be achieved with subcutaneous EEG needle electrodes, often referencing a nearby muscle to limit the number of channels required. One channel would have medial gastrocnemius referenced to anterior tibialis, the next vastus medialis referenced to rectus femoris, and so on. Abnormal activity may not, therefore, be localized precisely to one muscle. If such localization is vital, then each channel should be made to represent separate muscles, with two electrodes placed in each muscle. Fine-wire electrodes can also be used, with the active recording surface being a small bared tip. This is most useful for deep or small muscles (rhomboids, laryngeal muscles), especially when a more selective recording from a single muscle is vital. As the fine-wire electrodes record from a smaller area of muscle, EEG electrodes are preferred to maximize the chance of detecting neurotonic discharges.

#### **TECHNICAL PROBLEMS**

Acquiring accurate information quickly is important because it guides surgical decision-making. Several potential technical problems must be understood. Low nerve temperature is inevitable in IOM, leading to slowed conduction velocities and higher response amplitudes. Since temperature cannot be increased during IOM, the effect of low temperature must simply be kept in mind. Most analysis during IOM is monitoring for the presence or absence of a potential or a change in a potential at a nearby recording site. Cool temperatures during IOM will unlikely have a significant effect on these parameters. Low systemic blood pressure can reduce SEP and MEP amplitudes. Peripheral ischemia from a blood pressure cuff can also affect studies. If a tourniquet is in place for more than 60 minutes, it should be released for at least 20 minutes before beginning IOM studies. Since the operating room is an electrically hostile environment, it is imperative to remember that surgical instruments, beds, machines, and lights all contribute 60-Hz interference. Limiting fluores-

cent lights, electrical motors, or cautery devices during recording is helpful.

Anesthesia can have a major detrimental impact on IOM, especially the use of inhalational agents that suppress cortical excitability. For SEPs, this negatively impacts scalp recordings more than cervical spine or nasopharyngeal recordings. Anesthetic agents reduce the effectiveness of transcranial electrical stimulation in initiating a MEP. NAP recordings, however, are minimally affected by anesthesia. When recording directly from muscle, neuromuscular blocking agents should be minimized or not used at all; these agents may, however, be desirable for NAP, SEP, or MEP studies in which muscle artifact must be eliminated. Our preferred anesthetic regimen is intravenous narcotic and propofol with use of medium-acting neuromuscular blocking agents. Once adequate responses are obtained, low-level halogenated agents can be used. Both low-level inhalational agents and intravenous midazolam produce amnesia for the surgical procedure.

Stimulus artifact can be a challenge. Ensuring the electrodes are lifted out of a wet field is important. The lowest stimulus intensity at the shortest duration possible should be used to achieve supra-maximal stimulation. The distance between stimulation and recording electrodes can be increased if exposure in the surgical field permits this. Recording electrodes can be arranged in a monopolar fashion with G2 in adjacent tissue perpendicular to G1. Muscle artifact caused by volume conduction from nearby sources can also distort the NAP. Proper orientation of the electrodes and grounding must be assured. Neuromuscular blocking agents can be utilized to eliminate this artifact as well.

#### **PERIPHERAL NERVE LESIONS**

Peripheral nerve IOM is often performed to determine continuity across an injured segment of nerve or for precise localization of a peripheral nerve lesion.

In describing focal peripheral nerve injuries, there are two main classification systems. One, proposed by Sunderland,<sup>32</sup> uses anatomical distinctions, whereas the other, by Seddon,<sup>28</sup> utilizes the functional status of the nerve, that is, whether there is neurapraxia, axonotmesis, or neurotmesis. In neurapraxia, a functional block exists to conduction of the action potential along the nerve; the ultimate prognosis is favorable given the preservation of axonal and neural architecture. In axonotmesis, disruption of the axon occurs with some degree of intact neural structure, but the endoneurium is preserved. Recov-

ery requires regrowth of axons back to their target organ through the endoneurial tubes, following wallerian degeneration. Neurotmetic lesions involve both the axonal and neural structure, making regrowth of the axon nearly impossible. For up to 4–7 days after a nerve injury, the distal portion of the injured nerve will be electrically excitable. After that, wallerian degeneration will occur back to the level of the nerve injury. Axonal regeneration then may proceed from the lesion, moving distally at a rate of about 1 mm per day.

More complicated is the reinnervation of the end organ, which must occur for functional recovery. After axons reach a muscle, there may be a delay of several weeks to a month before reinnervation can be detected. This is usually first detected by electrophysiological means (nascent MUAPs), then by visible voluntary contraction.<sup>23</sup> Depending on the distance from the lesion to the end organ, a variable period of time must pass before clinical and electrophysiological signs of reinnervation become apparent. By the time it can be concluded that there is no reinnervation, the opportunity for a surgical approach to reinnervation (i.e., nerve grafting) may be lost since the best results are obtained when surgery is performed in the first 6–12 months. With a proximal sciatic lesion, 6–12 months or more would be required to conclude there is no reinnervation to the anterior compartment of the leg from a clinical or standard electrophysiological measurement. A technique for determining the likelihood of reinnervation (or continuity) after a peripheral nerve lesion at an earlier time-point is therefore useful for guiding surgical intervention when it will be most successful.

Surgical decision-making in peripheral nerve lesions is based on the determination of functioning axons across a lesion, or continuity. This may be proven by clinical examination, as some preserved motor or sensory function in the distribution of the nerve in question indicates a lesion in continuity. Preoperative electrophysiological assessment also contributes to this determination as the finding of voluntary MUAPs implies a lesion in continuity. If neither of the aforementioned clinical or electrophysiological findings are present, the lesion is thought to be “complete” clinically (i.e., there is no continuity proved) and often a surgical repair (nerve grafting) is considered. This is a challenge because there may not be the luxury of waiting for these clinical or electrophysiological signs of reinnervation to occur or not occur, before deciding on surgery. As previously discussed, there is a time window in which surgical intervention is more likely to be successful,

and this is typically shorter than the time it takes to detect signs of reinnervation (if it were to occur). In this setting, only intraoperative assessment can provide a timely determination of whether there is functional continuity across a lesion. Visual inspection is of great importance as nerve thickening and neuroma formation may suggest a lesion without continuity, although there is no visual way to reliably determine physiological continuity of axons, especially regenerating ones. The presence of a NAP across a lesion, however, remains the gold standard by which many determine nerve continuity and, therefore, the type of surgical approach. It is clear that a NAP can be obtained in the setting of a lesion that appears complete clinically by routine preoperative electrophysiological testing.<sup>22</sup> Lesions in continuity are treated with neurolysis and are not grafted; they have a high likelihood of having a good outcome. Lesions with no NAP transmitted are thought to have no chance of spontaneous recovery and are thus treated by grafting or nerve transfer.<sup>22,31</sup>

Nerve stimulation and recording is performed as described above. Stimulation is proximal to the lesion, with recording distally. Ideally, the recording electrodes are placed just proximal to, then in, and finally distal to the lesion. Recording a NAP over intact nerve (proximal to the lesion) helps as a control to ensure functioning of the whole IOM system. When a NAP is recorded across a lesion, continuity of at least 4000 axons is likely and a surgical procedure limited to neurolysis is typically performed.<sup>21</sup> In a study by Kline et al., approximately 90% of patients experienced a good outcome.<sup>22</sup>

If there is no NAP across a lesion, there are essentially three possibilities. First, there may be complete axonal disruption with no regenerating axons across the lesion. This would necessitate resection and a nerve grafting or transfer procedure. Second, there may be the potential for axonal regeneration that is being stunted by compression of fascicles by scarring within the nerve itself. An internal neurolysis can then be performed, allowing outgrowth of these regenerating axons. This carries with it some risk for neural damage and disruption of regenerating axons and is generally not performed. Unfortunately, distinction between these two possibilities is impossible electrophysiologically and must be made by the surgeon, taking into consideration the appearance of the nerve.<sup>22,27</sup> In some settings, although a NAP is recorded across the lesion, part of the nerve appears significantly injured and fascicular NAP recordings are helpful. Single fascicles are stimulated; those that demonstrate continuity are left



alone and those that do not are treated with primary repair or fascicular grafting.<sup>33</sup>

A third explanation for the lack of a NAP across a lesion is conduction block or neurapraxia. The preoperative electrophysiologic evaluation should help distinguish this, since signs of recent denervation would be minimal to absent, and CMAP amplitudes evoked distal to the lesion would be normal.

Neurapraxia that does not completely block all conduction through a lesion will lead to responses being recorded with both proximal and distal stimulation (across a lesion). Responses from the proximal site may be longer in duration (temporal dispersion), lower in amplitude (partial conduction block), and arrive at the recording electrodes with a longer latency than expected (focal slowing). Inching is a technique of stimulation at short, incremental steps across a lesion while the change in morphology and latency of the evoked waveforms recorded distally is assessed.<sup>5</sup> When inching at 1-cm increments, assuming a conduction velocity of 50 m/s, the onset of each successive waveform should be separated by 0.2 ms. As the main goal of inching is to localize more precisely focal lesions, it is useful in the intraoperative setting when this localization is not provided by preoperative electrophysiological studies.

Given the above information, it is clear that peripheral nerve IOM can be helpful when surgically approaching a peripheral nerve lesion in which the localization or continuity of the lesion is in doubt. The approach to and utility of IOM of the most common mononeuropathies is considered in what follows.

**Ulnar Nerve Entrapment at the Elbow.** Ulnar neuropathy at the elbow (UNE) is the second most common entrapment mononeuropathy, trailing only median neuropathy at the wrist (carpal tunnel syndrome). While IOM is not often used for UNE surgery, it can be useful in certain instances. The two main anatomical sites of compression at the elbow are the cubital tunnel, formed by the two heads of the flexor carpi ulnaris muscle, and the retroepicondylar groove between the medial epicondyle and the olecranon. The surgical approach to compression at these two levels is different: simple decompression with entrapment at the cubital tunnel, and ulnar nerve transposition or epicondylectomy if entrapment is more proximal in the retroepicondylar groove.

Preoperative electrophysiological studies may confirm UNE but not localize the lesion to one of these sites.<sup>13,23</sup> Factors that contribute to this include variability in anatomical location of these two poten-

tial entrapment sites, selective involvement of fascicles in the ulnar nerve, technical difficulties with overstimulation (especially at the below-elbow site), and anastomotic nerve connections. The degree of intraoperative electrophysiological abnormalities is often more severe than expected based on routine preoperative studies.<sup>22</sup> Intraoperative studies may even show abnormalities when routine nerve conduction studies across the elbow are normal.<sup>17</sup> Additionally, compression may be at a more distal site than expected.<sup>6,7</sup> Intraoperative ulnar nerve studies are therefore useful when localization is needed to guide the type and site of surgical intervention.

The ulnar nerve is usually easily exposed surgically. If possible, stimulation and recording should be performed on a normal portion of the nerve to ensure a working system. Then, recording proximally, the stimulating electrodes are placed at intervals closer, within, and distal to the area in question. An assessment is made for changes in amplitude, latency, and morphology as stimulation moves into the abnormal segment of nerve. Based on intraoperative ulnar nerve studies, the site of compression is most commonly at or just proximal to the retroepicondylar groove/medial epicondyle.<sup>2,17,22</sup> In fact, a 30-year study at Louisiana State University demonstrated compressive ulnar neuropathies localized to the epicondyle level in over 97% of cases.<sup>17</sup> Cubital tunnel localization was seen more frequently in other studies.<sup>5,7</sup> Based on these findings, the physician should begin stimulating across the epicondylar region. If no clear abnormalities are seen, the segment of nerve across the cubital tunnel should be assessed. If these sites are normal, it is important to realize that the ulnar nerve can rarely be compressed at sites distal to the cubital tunnel, within or as it exits the flexor carpi ulnaris.<sup>4,7</sup>

**Median Neuropathy at the Wrist.** Median neuropathy at the wrist is the most common upper-extremity entrapment neuropathy. Routine electrophysiological studies are excellent at confirming the clinical diagnosis of carpal tunnel syndrome.<sup>1</sup> As in UNE, intraoperative studies are rarely performed given the relative ease of the decompression procedure and the lack of uncertainty in localization.

In one approach to intraoperative median nerve studies, stimulation of the nerve was performed in 5-mm increments proximal to, through, and distal to the carpal tunnel with surface recording over the thenar eminence.<sup>2</sup> The most abnormal segment with respect to focal slowing or conduction block corresponded to the segment of the most abnormal-appearing nerve. In the remainder of cases, the slow-

ing involved two or more 5-mm segments. The site of the most abnormal conduction was within the first 10–20 mm just distal to the proximal border of the flexor retinaculum. Immediately upon release of the median nerve in the carpal tunnel, latencies have been noted to improve<sup>10</sup> or remain the same.<sup>37</sup>

Another technique has been described in which the median nerve is stimulated in the region of the carpal tunnel with recording of the sensory digital branches on the third digit.<sup>24</sup> This technique has demonstrated that the most abnormal segment (most conduction slowing and amplitude reduction) is the distal part of the carpal tunnel. This also correlates with the area of highest intracarpal tunnel pressure measurements.

**Common Peroneal Neuropathy at the Knee.** The common peroneal nerve can be compressed or damaged as it traverses the fibular head at the knee. Similar to median neuropathy at the wrist and UNE, localization with routine electrophysiological studies is usually possible. Intraoperative peroneal nerve studies can be performed for localization and to determine nerve continuity.<sup>2</sup> One large series of surgically treated common peroneal neuropathies revealed that often there is no transmission of a NAP across the lesion, leading to nerve graft repairs. Most patients in this series of 318 cases had suffered traumatic peroneal neuropathies. Nontraumatic cases with compression or entrapment at the knee (51 of 318) were more likely to have recordable NAPs (42 of 51) and thus undergo neurolysis as opposed to nerve grafting.<sup>18</sup>

#### USE IN BRACHIAL PLEXUS RECONSTRUCTION

Given the complexity of brachial plexus injuries in terms of anatomy and type of injury, intraoperative electrophysiological monitoring is essential to enhance clinical outcome. Brachial plexus injuries are typically classified as preganglionic, postganglionic, or a combination of both. The continuity of the spinal root is likely the most important factor in surgical planning because root avulsion is nonreversible with no chance for recovery spontaneously or with primary anastomosis or grafting procedures. In a suspected postganglionic injury, IOM is essential to determine the presence of axonal continuity at a time when CMAPs or voluntary MUAPs cannot be detected due to lack of distal axonal regeneration.

Preoperative evaluation is important to determine the degree of both vertical (root or plexus level) and horizontal (i.e., preganglionic vs. postganglionic) involvement, but available methods are not

always adequate to make this determination. Factors suggestive of preganglionic injury include: winging of the scapula due to serratus anterior weakness; presence of Horner's syndrome; or pseudomeningocele seen with myelography or magnetic resonance imaging (MRI). Unfortunately, myelography and MRI may not be able to clearly identify root avulsion in some cases.<sup>8</sup> The presence of sensory nerve action potentials (SNAPs) on routine NCSs in a flail limb is suggestive of a preganglionic lesion, but the absence of these sensory responses may represent either a postganglionic process or a mixed process with additional root avulsion. The presence of prominent fibrillation potentials in cervical paraspinal muscles also suggests root avulsion, but cannot determine the precise root level. After surgical exposure, visual inspection may reveal the anatomical or structural integrity of a spinal root or nerve. If, however, an avulsed root remains intradural or, as is frequently the case, is scarred, one may be misled into assuming functional continuity of that spinal root or nerve. In this case the functional continuity of the axons cannot be determined without IOM techniques.

SEPs have been the mainstay of determining root continuity. The presence of reproducible cervical or cortically recorded potentials is indicative of intact large-fiber sensory axons but does not provide information regarding motor axons. During surgery, baseline SEPs are recorded after stimulation of either an intact ipsilateral nerve or root or, alternatively, of the contralateral limb (usually median nerve), to assure the recording system is working properly. The absence of these responses from scalp recordings can be seen with excessive inhalational agents, although the cervical potentials should be minimally affected. The cervical potentials are generally less reliable, however, given the possibility of muscle artifact and the short distance between stimulation and recording sites, making stimulus artifact more of a confounder. Interaction with the anesthesiologist prior to beginning these recordings is critical to assure the best possible scalp responses. After surgical exposure, direct root stimulation is performed under the surgeon's direction, with recording over the scalp and cervical spine. In the recent past, continuity at the root level, based on the presence of a reproducible SEP, was believed to correlate with the continuity of the motor axons in the ventral root as well. In many cases, however, this proved not to be true in that grafting procedures led to no peripheral reinnervation. For this reason, following SEP studies, the ventral root axons are assessed by means of MEP studies. If no reproducible responses can be obtained when recording at the root level,

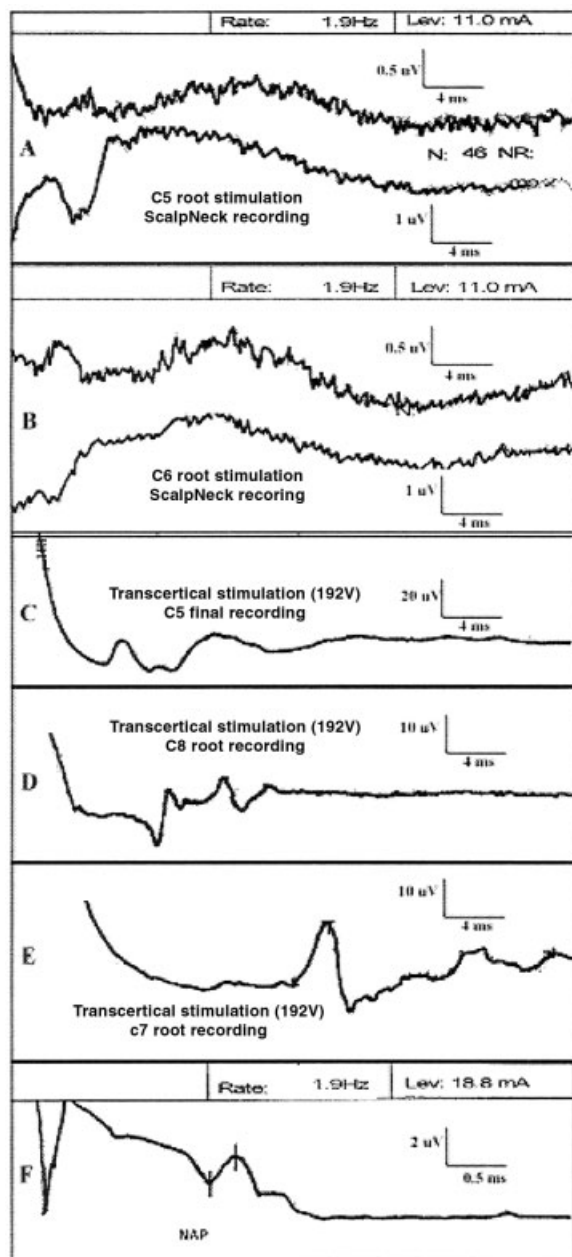
this suggests a lack of continuity of the motor axons back to the anterior horn cell, which would eliminate direct root grafting or anastomosis.<sup>3,35</sup> In this setting, alternative surgical approaches, such as neurotization and tendon or muscle transfers, may be performed. A reproducible MEP indicates ventral root continuity, which allows the surgeon to consider nerve grafting procedures. A potential pitfall in MEP recording is a volume-conducted response originating from nearby muscles rather than from the nerve itself. Use of a short-acting paralytic agent is necessary in this setting; volume-conducted muscle responses will be suppressed, whereas MEPs directly from the nerve are unaffected.<sup>35</sup> The assessment of SEPs and MEPs is then carried out on the remaining proximal roots or stumps that are not clearly avulsed on visual inspection.

Once it is determined whether the nerve roots are in continuity with the spinal cord, attention turns to defining functional conduction through the peripheral segments that appear to have been injured. Although gross or microscopic inspection can give the surgeon some indication of fascicular preservation, IOM studies are critical to determine both the continuity across the lesion and the proximal extent of the process. This is best performed with NAPs. If, on visual inspection, there is a scarred but anatomically intact segment, neurolysis only is performed when a NAP is present. If there is no reproducible NAP, the lesion is generally resected, followed by nerve repair or grafting procedures. Determining the proximal extent of the resection is critical in that a functional fascicular structure in the proximal stump without intervening scar tissue will allow the greatest chance for distal growth and reinnervation. In a pure postganglionic lesion, a NAP should be present with stimulation and recording proximal to the lesion. Sequential recording is then performed moving distally at approximately 1–2-cm intervals until the response is lost, thus identifying the most proximal extent of functioning axons. At that point the resection is performed followed by the grafting procedure of the surgeon's choice. It is important to combine NAP with SEP and MEP recording because a NAP could still be generated by sensory axons in the setting of a ventral root avulsion, and this would lead to a futile attempt at regeneration if a direct grafting procedure was performed. Finally, once a nerve lesion is identified, it may be clear that certain fascicles are disrupted whereas others have preserved conduction. Internal neurolysis with split repairs may be necessary in this setting and NAP recordings to specific fascicles are critical for a successful outcome.<sup>31</sup>

### Illustrative Case Report

The following case presents the use of these IOM techniques. A 42-year-old man presented with a flail left arm after a snowmobile accident. Six months after the injury, complete loss of motor and sensory function persisted in the arm. On clinical examination voluntary contraction was possible only in the rhomboid, trapezius, and serratus anterior muscles and diffuse sensory loss was present throughout the limb. Stretch reflexes were absent. A Tinel's sign was present in the left supraclavicular region, radiating to the thumb. There was no evidence of Horner's syndrome. Routine NCSs of the left arm revealed absent median and ulnar motor responses and a low-amplitude median SNAP. The lateral antebrachial sensory response was absent. Needle examination showed dense fibrillation potentials with no MUAPs activated in muscles in the left upper limb plus infraspinatus. Rhomboids were normal as were the middle cervical paraspinals. Prominent fibrillation potentials were noted in the low cervical paraspinal muscles. These findings were consistent with a severe left pan-brachial plexopathy with mixed preganglionic and postganglionic injury and probable complete root avulsion affecting the lower segments (C8, T1, and possibly C7). There was likely at least partial preservation of the C5 root, although this was difficult to predict with absolute certainty as in some cases the rhomboids may be innervated by C4. A computed tomography myelogram was consistent with left C8 and T1 nerve root avulsions. It was felt that he likely had intact outflow from C5 and C6. The continuity of C7 was uncertain, but given the serratus anterior activation, this was likely to be intact. Reconstructive surgery was indicated with IOM to determine root continuity and assist with surgical planning.

After surgical exposure, visual inspection suggested that the C5, C6, and C7 roots were intact, probably with significant postganglionic injury. The C8 and T1 roots were visibly avulsed. Intraoperative SEP testing with stimulation of the C5 and C6 roots showed reproducible responses (Fig. 1A and B). Motor evoked potentials were also present on C5, C6, and C7 roots while under a short-acting paralytic agent (Fig. 1C–E). This confirmed that there was both motor and sensory root continuity at C5 and C6 and at least motor root continuity at C7. Attention then turned to determining whether there was continuity across the injured brachial plexus. No reproducible response could be recorded across the upper or middle trunk segments, but a NAP was present stimulating and recording proximal to this



**FIGURE 1.** Intraoperative recordings during brachial plexus exploration and reconstruction. SEP recording over the scalp and neck, respectively, with direct intraoperative C5 root stimulation (A) and C6 root stimulation (B). The presence of the response supports C5 and C6 sensory root integrity. Transcranial electrical stimulation with direct MEP recording over the C5 root (C), the C6 root (D), and the C7 root (E) supporting integrity of C5, C6, and C7 motor roots. Nerve action potential with stimulation and recording proximal to the lesion (F); no reproducible response could be recorded across the lesion.

level (Fig. 1F). Based on these findings the following grafting procedures were performed: C5 to axillary nerve; C6 to musculocutaneous nerve; and C7 to radial nerve. Also performed was a transposition of

the contralateral C7 root to the left median nerve via a vascularized ulnar nerve graft. In this particular case, IOM confirmed continuity of the C5–C7 roots, which were then used as grafting vehicles, allowing the contralateral C7 root to be used in an attempt to achieve more distal reinnervation. It also helped to define the proximal extent of the nerve injury.

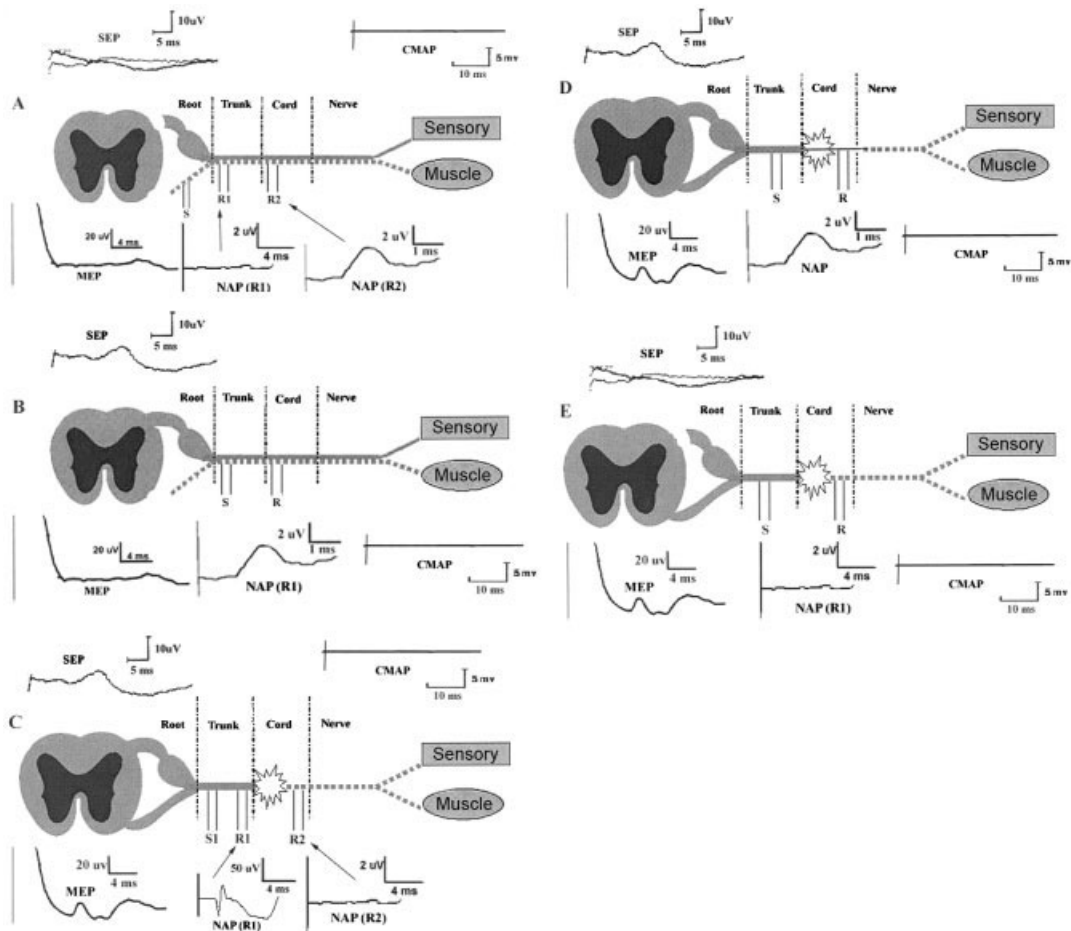
#### Expected Findings with Various Injuries

Figure 2 shows various injuries along with the expected IOM findings. Figure 2A and B shows ventral root avulsion, eliminating a grafting procedure, even with the presence of an SEP, as in Figure 2B. A complete postganglionic injury is depicted in Figure 2C. The SEP and MEP are present, whereas a NAP across the plexus is not present. Stimulation and recording in the proximal plexus yields a NAP, identifying the proximal extent of the lesion. In this setting, nerve grafting/transfers or end-to-end anastomosis would be appropriate. If a NAP is present across elements of the brachial plexus (Fig. 2D), only neurolysis of that segment would be performed. A mixed lesion with sensory root avulsion and severe postganglionic injury is shown in Figure 2E. In this case, the utility of performing both MEP and SEP studies is demonstrated, as absence of a SEP without testing of the MEP could be interpreted as representing a low likelihood of a successful grafting procedure when, in reality, this is likely to be most beneficial.

#### USE IN SELECTING FASCICLES FOR BIOPSY

Rarely, given a focal or multifocal process, will a nerve biopsy be required of a proximal or nontraditional nerve (i.e., not a whole sural or superficial peroneal). Targets include nerve root, brachial plexus, or fascicles of proximal or distal nerves. These biopsies are useful, leading to diagnoses such as lymphoma, focal inflammatory neuropathy, or sarcoidosis, all of which have varying treatments and prognoses. Clinical examination, preoperative electrophysiological testing, and imaging studies with 3-Tesla MRI can all localize pathology to certain nerves or parts of nerves (i.e., the peroneal division of the sciatic nerve). During surgery, however, when faced with actually removing sections of these nerves, it is crucial to remove the part of the nerve with the greatest chance of pathological diagnosis and least chance of causing a new postoperative deficit. Visual assessment made by the surgeon upon exposure of the nerve at the time of biopsy is helpful. Electro-





**FIGURE 2.** Expected intraoperative recording with various lesions of the roots or plexus. **(A)** Complete ventral and dorsal avulsion. Preservation of nerve action potential (NAP) due to intact sensory fibers, with MEP and SEP absent. **(B)** Ventral root disruption with preservation of dorsal root. Preservation of NAP and somatosensory evoked potentials (SEP) with root stimulation but MEP absent. **(C)** Complete postganglionic lesion. Preservation of SEP, MEP and NAP proximal to lesion. No NAP recorded across the lesion, indicating no evidence of functional axons across the lesion. **(D)** Severe postganglionic lesion but with some regeneration through the injured segment. Note the presence of all responses, with the exception of the compound muscle action potential amplitude, given there has not yet been end-organ reinnervation. **(E)** Mixed preganglionic and postganglionic lesions.

physiological testing can further add to this important assessment.

Just prior to biopsy, direct stimulation is applied to the individual fascicles in question. An assessment is made by the presence or absence of a downstream twitch in muscles innervated by the nerve, or by recording from muscle (surface or EEG needle electrodes) or nerve (as a NAP) as described earlier. This allows for the identification of functioning and nonfunctioning fascicles. In this manner, a biopsy can be performed with the highest diagnostic yield and lowest risk.

#### USE IN OPERATING ON NERVE TUMORS

Peripheral nerve tumors are rare. These are broadly separated into neural sheath tumors and nonneural sheath tumors. Examples of the former include be-

nign entities such as neurofibromas (with or without neurofibromatosis type I) and schwannomas. Sarcomas (neurogenic, fibrosarcoma, spindle cell, synovial, or perineurial sarcomas) are malignant neural sheath tumors. Nonneural sheath tumors include ganglion cysts, lipomas, hypertrophic neuropathy (although some of these may be inflammatory), vascular tumors, and desmoid tumors. Metastatic carcinomas can affect nerve; most commonly this is from a lung or breast primary tumor. The location for these peripheral nerve tumors varies, with the brachial plexus and upper extremity being most common, followed by the lower extremity and, uncommonly, the lumbosacral plexus.<sup>19,20</sup>

The use of NAP recordings can be helpful intraoperatively. A stimulator can be used to localize



peripheral nerve if the architecture or anatomy is confusing. Functioning fascicles are identified in order to protect them if possible, and thereby limit postoperative neurological deficit. In most cases, complete tumor removal takes precedence and fascicles may need to be sacrificed. Fortunately, fascicles with tumor involvement are usually nonfunctioning.<sup>31</sup>

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