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Up and Down the Spinal Cord: Intraoperative Monitoring of Sensory and Motor Spinal Cord Pathways

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Summary: Monitoring of spinal cord function during certain orthopedic and neurosurgical procedures is done to reduce the likelihood of neurologic complications. This article is based on intraoperative experiences gained at Duke University Medical Center since 1978. Both ascending sensory (up) and descending motor (down) data can be evaluated to assist in improved patient outcomes. Refinements in technique and better understanding of the neural generators of evoked potentials obligate the components to have improved sensitivity and specificity of spinal intraoperative monitoring. An additional improvement has been the intraoperative use of motor evoked potentials. This discussion deals with a description of specific responses obtained following lower-limb mixed nerve stimulation in terms of neural generation, influences of rate and intensity, and anesthetic effects. The techniques and advantages of bipolar epidural recording and stimulation are discussed. Motor tract stimulation via the same epidural electrodes used for recording of sensory components is described. Case reports are presented to emphasize major points. **Key Words:** Intraoperative spinal cord monitoring—Lower extremity somatosensory evoked potentials—Motor evoked potentials—Spinal cord stimulation.

Electrophysiologic monitoring of spinal cord function is requested when a surgical procedure poses a risk for a postoperative neurologic sequelae. The various techniques of monitoring spinal cord physiology are directed at demonstrating physiologic stability (or lack thereof). An impending lesion may be averted if appropriate action can be taken while the changes are still reversible. If complications cannot be avoided, such monitoring may aid in understanding the causative mechanisms involved. This is because in long procedures it may be otherwise difficult without monitoring to attribute a specific act to an unfortunate outcome.

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Early reports of intraoperative spinal cord monitoring appeared in the 1970s (Nash et al., 1977; Engler et al., 1978). Somatosensory techniques were applied to patients undergoing corrective surgery for scoliosis. Refinements in instrumentation and technique have led to increased sensitivity and specificity relative to which changes in which components are of greater importance, producing fewer "false alarms" (meaning a report to the surgeon of a significant change implying iatrogenic neurologic injury when, in fact, such has not happened). False alarms usually lead to unnecessary prolongation of surgery with a resultant increased exposure of the patient to anesthesia and likelihood of complications and/or discontinuance of needed surgery.

Intraoperative spinal cord monitoring is indicated in those procedures that have a known or anticipated increased risk for producing an iatrogenic lesion in the perisurgical period. These include neurosurgical procedures for intra- and extramedullary tumors (both primary and metastatic), arteriovenous malformations, syringomyelia, acute traumatic or slowly progressive spinal cord compression, herniated thoracic disks, and release of tethered cord. The orthopedic deformities include scoliosis, kyphosis, and kyphoscoliosis; the more severely curved and/or rigid (congenital) forms usually having a higher incidence of neurologic complications postoperatively.

PROCEDURES

The intraoperative monitoring procedures should be considered a logical extension of the procedures and techniques used routinely in the diagnostic laboratory. Electrode locations, most stimulation parameters, and the components elicited are similar to diagnostic studies.

The sequence of procedures will be presented in the chronologic order likely to be used in a routine intraoperative case. In the early stages of surgery, only those components recorded from surface electrodes can be evaluated. As surgery progresses, it is feasible, and at times highly desirable, to place stimulating or recording electrodes nearer to the spinal cord via the surgical opening. There are definite advantages to the latter that will be discussed in terms of increased specificity and sensitivity.

The intraoperative monitoring begins with a preoperative baseline study. The techniques we use are essentially those described in the American Electrographic Society Guidelines on Clinical Evoked Potential Studies (1992).

Stimulation

Stimulation is carried out with 100-μs rectangular pulses applied to the posterior tibial nerve at the ankle. Exceptions include amputations, fractures, etc., making this site unavailable. In such conditions, the common peroneal nerve at the knee or femoral nerve in the groin may be used.

In the diagnostic laboratory, a stimulus intensity sufficient to produce a motor contraction of the extension muscles of the toes is applied. Usually, this is greatest in the large toe, but other toes may be involved. Increasing the stimulus intensity will increase the amplitude of the resultant popliteal fossa response, spinal response, and subcortical P31 components. These response amplitudes increase in a linear fashion with stimulus intensity until they reach a maximum, when 100% of the axons in the conducting pathway are depolarized by the stimulus (see Fig. 1). In the diagnostic laboratory, 100% depolarization is not reached due to unacceptable levels of pain.

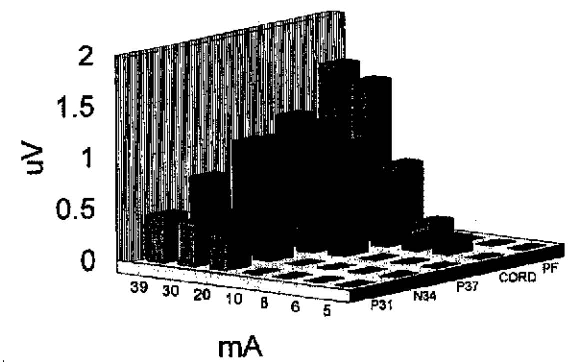


FIG. 1. Typical amplitudes of PTN-SSEPs to constant current stimulation at varying intensities. In this and the following illustrations, unless otherwise noted stimulation parameters are: rate = 5.4 Hz, duration = 100 μs, intensity = motor threshold × 2; recording parameters are: passband = 30–3,000 Hz, sweep = 80 ms, number of stimuli = 1.5–3 K. Between 39 and 20 mA, all responses (PF, cord, P31, and N34) show linear decreases of amplitude with the exception of the P37. The P37 does not attenuate until there is a marked drop in PF amplitude. The spinal cord responses (bipolar epidural electrode) are the most persistent at low stimulus levels. The anesthetic-resistant subcortical components are maximized by higher stimulus levels that is required to produce a maximal P37 component.

The exact number of milliamperes required from the constant current stimulator to elicit a motor response depends not only on the surface area of the electrode but its proximity to the nerve. The larger the surface area, the lower the current density (given a constant number of milliamperes). Subdermal needle electrodes (near nerve needle stimulation) require the least amount of current, primarily because of their proximity to the nerve. Needle electrodes have certain advantages, particularly in long surgical cases in which there may be concern that electrode paste or gels may dry out, producing higher and higher impedances. The maximum stimulus intensity is a function of the maximum available voltage output (usually 200–400 V) of the stimulator, and if stimulating electrode impedances are high (>5 kohms), effective nerve trunk stimulation may not occur because the maximum voltage output may have been reached (Ohm's law). Needle electrodes have their own theoretical hazards as a potential return path for electric cautery currents if there is a defect in the ground circuitry of the electric cautery device and/or loss of stimulator or amplifier isolation.

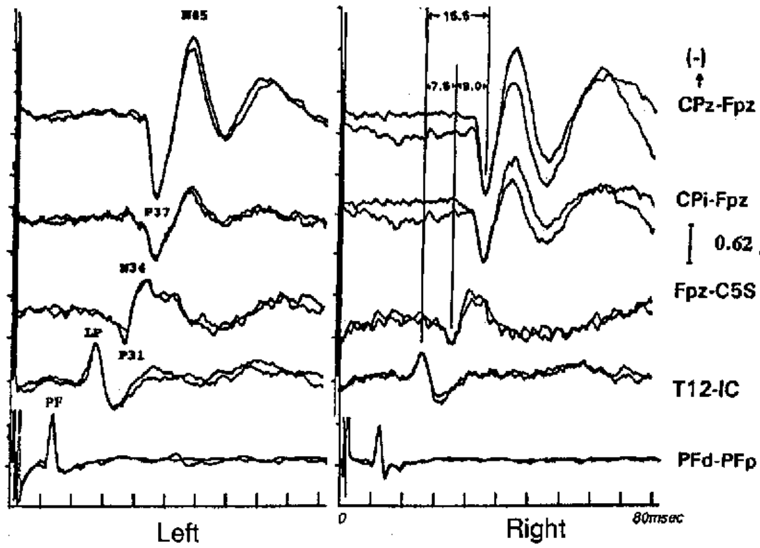


FIG. 2. PTN-SSEP recorded by "Guidelines" parameters. Major components are labeled PF, LP, P31, N34, P37, and N45. See text for further discussion.

Preoperative Evoked Potential Components

Tibial nerve stimulation classically elicits the following responses (see American Electroencephalographic Society, 1992, and Fig. 2).

Popliteal Fossa Response

The popliteal fossa (PF) response is a triphasic action potential recorded in the PF at the back of the knee. The posterior tibial nerve ascends through the midline of the knee. For a bipolar derivation, two electrodes are applied, with the first electrode attached 2 cm above the popliteal crease and connected to the negative input of the amplifier. A second, more cephalad electrode, is placed in the midline 3 cm rostral to the first electrode. This configuration gives rise to a triphasic action potential with an initial positivity, followed by a major negativity, and followed by a small degree of positivity. Both orthodromic and antidromic action potentials contribute to the PF potential.

Lumbar Potential

The lumbar potential (LP) is a stationary potential, generated by internuncial neurons usually at the level of the 12th thoracic vertebra. When recorded referentially to an iliac crest or contralateral knee reference, a primarily monophasic event is recorded. Embedded in the stationary LP response is a lower-amplitude traveling wave of dorsal column generation. The stationary potential is usually largest at the T12 level but occurs at the same latency at higher and lower electrode placements but with lower amplitude. There is an anterior–posterior dipole that is negative at the skin of the back and positive at the umbilicus. The anterior positivity is usually of low amplitude.

P31 Response

The P31 response is a far-field positive response, recorded from electrodes over a broad region of scalp. The P31 is isopotential at FPz, Fz, and CPz, as well as CP3 and CP4. It must be recorded referentially because scalp–scalp bipolar derivations produce in-phase cancellation of both the P31 and the later N34 component. Any distant reference is suitable; however, a cervical location is commonly used. This often misunderstood potential, when recorded in a neck–scalp derivation, has been called the "neck potential." This misnomer is based on the assumption, or at least implication, that it is recorded from the neck electrode. A neck-to-noncephalic reference derivation fails to reveal any identifiable P31-N34 component (see Fig. 3). Thus, although the potential is generated subcortically and perhaps close to the neck, it is not recorded by a neck electrode. It is thought the P31 may be an analog of the median nerve P14 response representing a lower pontine medial lemniscal-generated component.

N34 Response

The N34 response is closely associated with the P31 and is by definition negative, occurring at an average latency of 34 ms. It has similar distributional

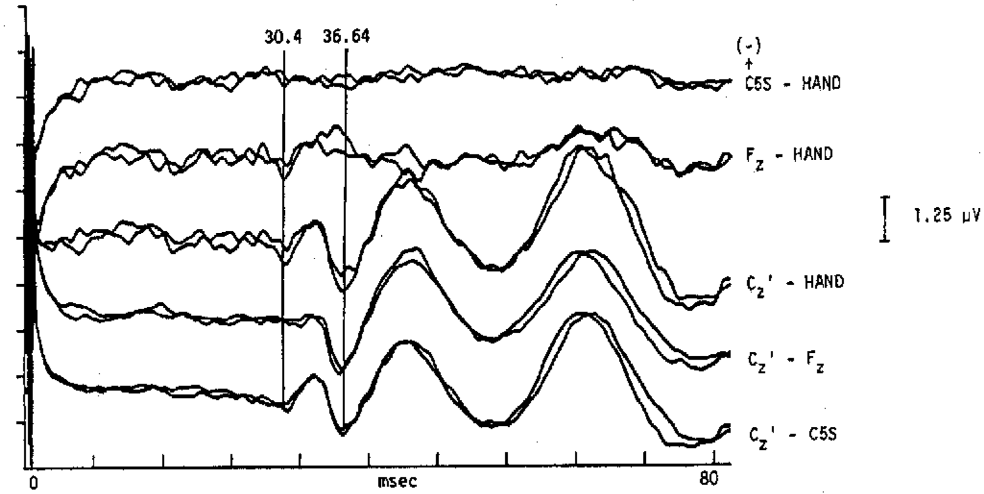


FIG. 3. Referential (hand) and bipolar derivations of scalp and neck potentials following posterior tibial nerve stimulation. The bottom channel reveals a low-amplitude P31 (30.4 ms) and an unlabeled N34 followed by a P37 (36.64 ms). The N34 is greatly attenuated in the scalp-scalp derivation of Cz'-Fz (and in some individuals is absent). The P31 and N34 are far-field scalp-recorded events that largely cancel by in-phase common mode rejection in scalp-scalp derivations. The neck-hand (C5S-HAND) derivation shows essentially no potential, indicating there is little recordable activity at C5S. C5S is effectively an inactive noncephalic reference for lower limb stimulation.

characteristics to the P31. The N34 may be analogous to the N18 of median nerve origin (MN-SSEP). Although the P31 and N34 are absent in the minority of normal subjects, they are important potentials particularly for operative monitoring for they are relatively unaffected by inhaled, halogenated anesthetic gases.

P37 Response

The P37 response, the last component of note, is, by definition, positive, occurring at approximately 37 ms. The absolute latency is a direct function of patient height. It is unfortunate that this response, which is relatively state-independent in the awake or sleeping patient, is markedly affected in both amplitude and latency by the majority of inhalation agents and thus has limited use unless one has rigid control over the anesthetic protocol. Further, it is markedly affected by rate of stimulation with attenuation of at least 80% when rates of 15/s or higher are used.

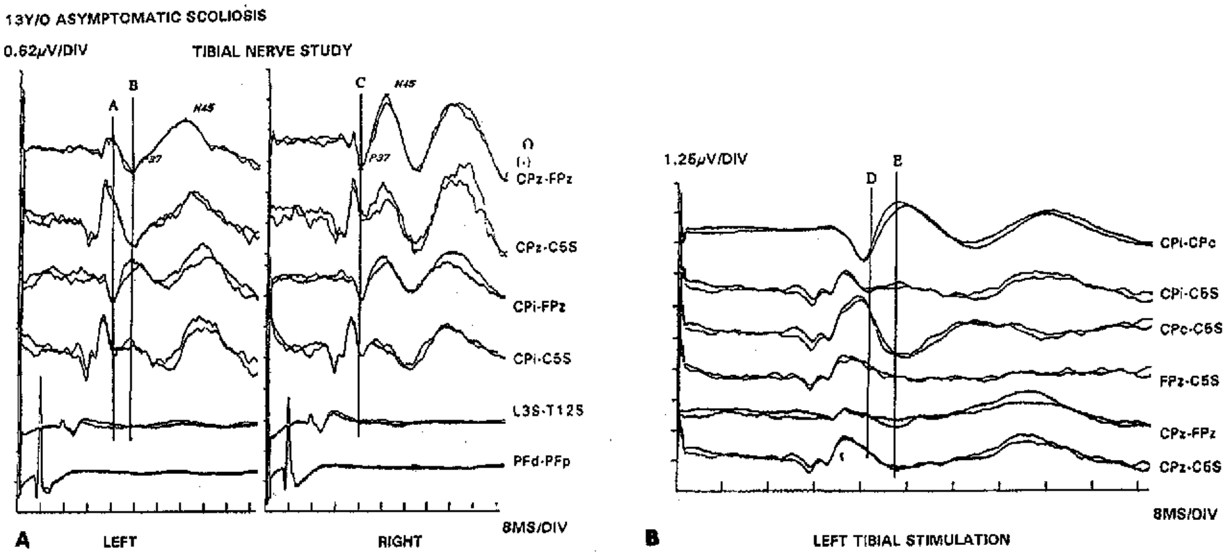
Following the P37 is the N45, which is partially state-dependent even in the diagnostic laboratory. In the surgical environment, it has all the weaknesses of the P37. It is critically important to obtain baseline studies so that one can anticipate unexpected variance or severe pathology. It is important to be aware of unexpected findings prior to surgery and to remember that all somatosensory studies are sensitive to the degree that they may be markedly abnormal in the absence of abnormal clinical findings. The interpretation of absent or markedly atypical responses as artifactual versus valid is difficult in the rush of preparation for surgery. On occasion, one may experience the absence or marked asymmetry of the midline P37 response, which may be normal, or at least symmetrical, when recorded from parasagittal CP3 and CP4 locations (see Fig. 4A). Whether findings such as those present in Fig. 4A represent an atypical variant or subclinical pathology is unknown. The patient whose data are seen in Figs. 4A, B, and C was normal by detailed neurologic examination and had uneventful orthopedic surgery and recovery.

Intraoperative Considerations

Baseline Data

In the operating room, the technologist evaluates electrode impedances and continuity of those left in place from the preoperative study for sufficiently low impedances. Mechanical stability is confirmed by checking the strain relief for both the primary and redundant secondary electrodes placed at each recording site. The technician, who is truly a part of the "operating team," should expect to be helped by other operating room personnel. In return, the electrophysiologic technologist should be ready to assist others.

It is important to discuss with the surgeon and the anesthesiologist the goals of the current surgery, the



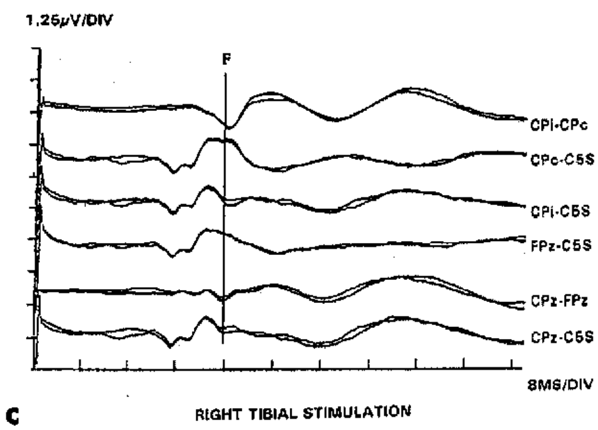


FIG. 4. A: Preoperative PTN-SSEP study in an asymptomatic 13-year-old girl of 4'10" stature. The midline-derived P37s are markedly asymmetrical in absolute latency (5.65 ms). The spinal-to-P37 interpeak latency to left tibial stimulation is abnormally prolonged at 23.57 ms. The asymmetry involves not only the P37 but also the N45 and subsequent components. The asymmetry is not a contaminant of frontal "reference" activity as evidenced by a similar asymmetry in the CPz-C5S derivation. Responses in channels 3 and 4 are entirely normal and symmetrical when recorded from the ipsilateral scalp (CPi-Fpz). The line marked "A" taken through P37 recorded at the ipsilateral scalp has a latency of 32.29 ms. "B" taken through the P37 recorded at the midline (CPz-Fpz) occurs at 38.86 ms. "C" is drawn through the unambiguous P37 responses to right tibial stimulation. The right tibial latency of both the midline and ipsilateral P37s are essentially the same, occurring at 32.66 ms in this individual of short stature. A partial explanation of these findings is illustrated in (B) and (C). **B and C:** More of the atypical midline distribution of the cortical components shown in (A). In (B), line "D" is drawn through the major positivity in the CPi-C5S derivation. The line goes through the point tagged as the P37 in (A) in the third channel from the top. Note at the midline there is no positivity in either CPz-FPz or CPz-C5S. The major valley in CPi-CPc is dominated more by negativity at CPc (see CPc-C5S) than positivity at CPi. The response recorded in the CPi-CPc derivation has been described as a dipole by some, but its major early deflection (P37?) rarely occurs exactly at the latency of the midline P37. It may lead or follow the P37. Further, either the contralateral negativity or ipsilateral positivity may be missing, suggesting possible separate neural generation of these components. Line "E" is drawn through the point labeled as P37 in the top channel of (A) (left). Line "F" is drawn through the normally distributed P37 recorded following right tibial stimulation.

type of potential neurologic damage, and the ideal anesthetic combinations to maximize quality intraoperative neurophysiologic data. It is not uncommon that the ideal goals of the anesthesiologist, surgeon, and electrophysiologist are incompatible, and compromises must be accepted. This may require, on occasion, anesthetic agents that place limitations on the quality of the electrophysiologic data. Under such circumstances, the presence of low-quality data must be addressed frankly with the surgeon and anesthesiologist.

Baseline data, obtained shortly after induction, should use essentially the same protocol as that used in the preoperative study. Recordings of relatively artifact-free data should be obtained, inspecting peripheral (popliteal fossa), subcortical (P31, N34), and cortical (P37) components. LPs are not obtained at this stage because the recording electrodes would be in the sterile field. Sterile electrodes could be placed by the surgeon, but soon they would become a problem, since they would encroach on the surgical field.

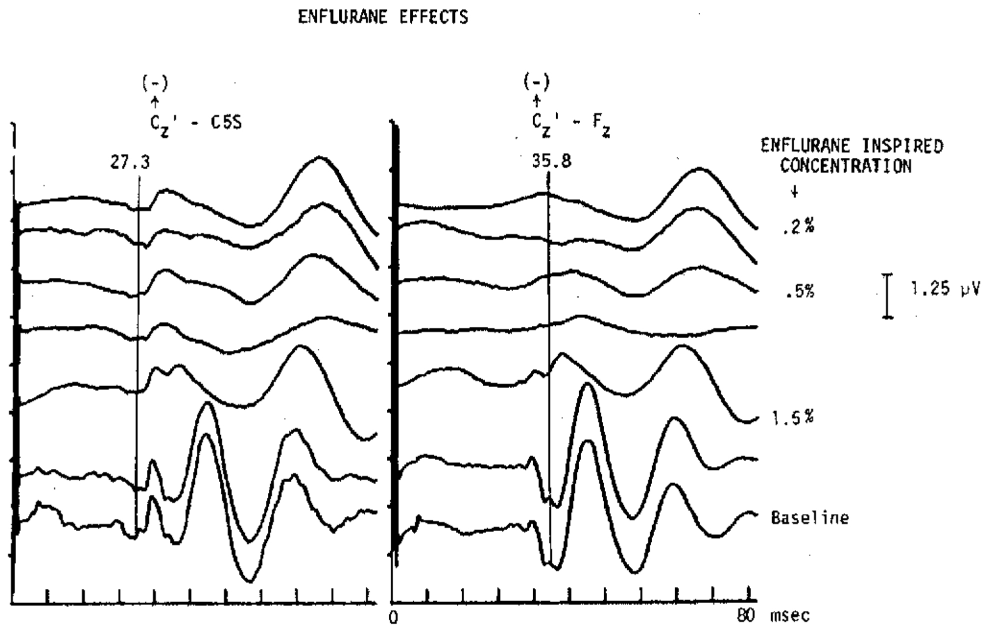


FIG. 5. Effects of enflurane (Ethrane) anesthetic on scalp–neck (left) and scalp–scalp (right) responses. Clock time progresses from bottom to top. Inhaled concentrations are labeled at right. Tissue concentrations lag inhaled concentrations by many minutes until equilibrium is reached. The P37 (right, 35.8 ms) is essentially abolished at higher concentrations. The P31 (left, 27.3) and to a greater degree the following N34 are attenuated but maintain a recognizable morphology and definable latency.

Anesthetic Agents

A balanced anesthesia of nitrous oxide and narcotic usually has minimal effects on the P37 latency. At a higher concentration, some amplitude effects have been reported. Unfortunately, hypertensive responses to surgery leading to increased blood loss may require the use of hypotensive agents. Although various antihypertensive agents are available including nitroprusside, some prefer to use inhalational agents such as isoflurane. These gases have the effect of attenuating the amplitude of the cortical P37 and delaying the latency (McPherson et al., 1985). [Further, they greatly attenuate the compound muscle action potentials (CMAPs) elicited by cortical or spinal stimulation presumably due to blockage at the level of the spinal interneuron or motor neuron (Zentner et al., 1992).] Usually, changes induced by anesthesia cannot be distinguished from those produced by neuropathic effects. When such changes occur, one can only say that they are consistent with a given anesthetic agent, but one cannot exclude additional (pathologic) factors. Some patients are far more affected by a given agent at a given concentration than others.

It is for these reasons that subcortical responses become important because spinal responses, P31 and N34, are usually minimally affected, even when the cortical response is obliterated (see Fig. 5). Unfortunately, a small but significant number of normal controls will not have a useful subcortical complex to follow, and it is in these cases in particular that we have found value in the use of an epidural electrode to record spinal responses.

Intraoperative Evoked Potential Components

Spinal Responses

Although surface-recorded spinal responses are difficult to obtain in the operating room, spinal responses may be the most important information obtained during the intraoperative period. Because they are recorded from a site just above the surgical zone, they arise prior to dorsal column or thalamic synapses. As a result, these responses are less affected by rate of stimulation or anesthetic agents. Various workers have used differing techniques to obtain responses from the spinal cord. Transcutaneously placed cervical needle electrodes, screw electrodes placed in dorsal processes of vertebral bodies, and needle electrodes placed in the interspinous ligament near the dura have all been utilized. They have in common the use of a referential technique with a reference electrode in the skin near the recording electrode.

Due to a serendipitous observation, we began using a bipolar platinum electrode in 1979. We were requested to obtain somatosensory scalp responses from a patient with intractable pain with an implanted epidural electrode overlying the dorsal columns (Shealy et al., 1970; Fox, 1974). This electrode had been placed for use with a dorsal column stimulator for pain control. The electrode in the epidural space led to a coil of wire placed subcutaneously. The stimulator was another wire coil attached to the stimulator device connected to wall current. In its intended use, the patient would place the primary coil of the stimulator over the back. Transcutaneous induction, from the primary to the secondary coil, allowed regulated current to flow in the epidural electrode (Brummer and Robblee, 1983). The current level was low and the frequency was high in the range of 100 Hz. The patient was of the opinion that the device was not delivering appropriate stimuli to his dorsal column. The surgeon believed the device was working but wanted to document this and felt that sensory evoked responses from the cortex would demonstrate the intactness of the stimulator.

The stimulus rate was lowered to 5.4/s, and recordings were begun to detect a time-locked scalp response. The intensity of stimulation was gradually increased, and the patient was instructed to indicate if excessive discomfort was encountered. As the stimulus intensity increased, the patient commented that his lower extremities were jumping.

Since this patient had initially had a standard tibial nerve somatosensory evoked response with recording electrodes in the PF as well as scalp electrodes, the PF electrodes were added to the montage. Bilateral activity was clearly present with both a nerve action potential and a CMAP occurring sequentially (as revealed by subsequent studies).

Since these epidural electrodes were available to us, and a number of our neurosurgical and orthopedic residents and senior staff were experienced in their placement, it was easy to begin using these techniques. Placement of the epidural electrode requires approximately 5 min of surgical time and is accomplished by removal of the interspinous ligaments at a level one above the surgical exposure.

Epidural Electrodes

Epidural electrodes are available from several commercial sources. The electrodes are fabricated from platinum, usually in the shape of a rectangle or circle. The surface area we use is 0.40 cm^2. The contacts are separated by 8 mm and are embedded in a molded footplate of thin flexible Silastic material. The wire leads to the electrode contacts are sufficiently long to be draped over the sterile coverings and terminate in pinjacks attached to an additional extender cable, which connects directly to the headboard or stimulator (see below). The electrode is placed under the laminal arch on the epidural surface with electrode contacts facing down toward the dura. The wire leads are then bent toward the head and secured in place with a single suture to provide strain relief. They are also attached to a towel clip to provide additional strain relief.

The Epidural Response

The spinal response may be recorded from either of the two electrodes in the Silastic footplate referenced to a nearby skin surface electrode or more commonly a bipolar response using the two epidural contact points. Advantages of the bipolar response are several. In addition to improved in-phase cancellation of noise components due to the close (8-mm) interelectrode spacing, there is absence of myogenic activity. Cardiac artifact, although large, is suppressed by in-phase cancellation, but in-phase cancellation also reduces some of the slower, more widely distributed evoked spinal activity. What remains in the bipolar response is a complex, polyphasic ring of activity with from 5 to 15 or more reproducible components (see Fig. 6). This ring of activity may extend past the onset of the P37 response recorded from scalp electrodes (see Fig. 7). The exact origin of this polyphasic burst of activity is unknown, but it may represent internuncial neuronal chatter within the spinal cord rather than a population of ascending nerve action potentials. If true, the response would be a combination of tract origin and local gray matter activity.

Spinal Evoked Motor Activity

Evoked motor activity can be elicited by stimulation through the same epidural electrodes previously described for recording of ascending sensory responses (see Fig. 8). Safety considerations are of paramount importance. Electrodes must be made of platinum for other metals may become toxic when currents are applied due to the dissolution of neurotoxic ionic elements into solution (Pudenz et al., 1975; Brummer et al., 1983). "A charge density of 400 $\mu C/cm^2_{(real)}$/phase can be absorbed by faradaic reac-

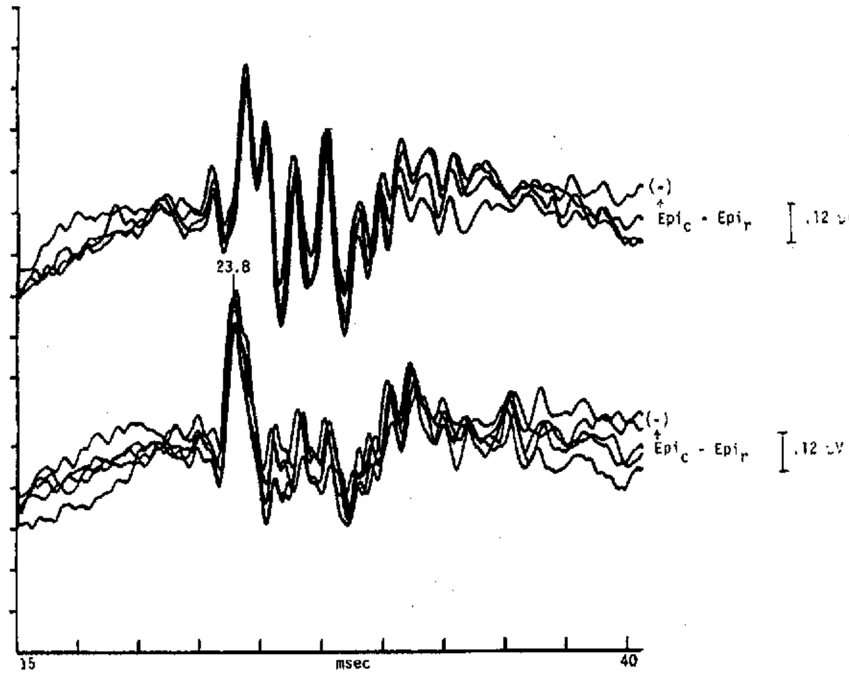


FIG. 6. Bipolar epidural responses to alternating right (top) and left (bottom) posterior tibial nerve stimulation. The epidural electrode is under the laminal arch of T3. Minor asymmetries between left and right responses are common and apparently related to position of the blindly inserted electrode, which may not be in the exact midline. Multiple responses are overlaid. The caudal epidural contact (Epi_c) is connected to the negative input of the amplifier, producing an upward deflection. The rostral contact (Epi_r) is connected to the positive input. Passband is 30–1,500 Hz; 500 stimuli/average; 15 ms poststimulus delay; 25 ms display; rate = 23.4/s; acquisition time/average = 21.4 s. The largest component is approximately 0.6 μV, and the fundamental frequency of the response ranges from 600–900 Hz. In this patient, it is 840 Hz.

tions of surface-adsorbed species, but a small part may be lost due to metal dissolution." Milliamps times milliseconds equals microcoulombs, the surface area of polished platinum is multiplied by 1.4 to determine the true histochemical surface area, and phase indicates a biphasic pulse. Biphasic pulses are utilized to avoid a capacitance buildup of charge density in tissue.

We obtained motor responses as low as 5 μC/$cm^2_{(real)}$/phase, and thus we were well below the threshold for tissue damage. Further, our stimulation rates were well below the 50/s used by Pudenz et al. (1975) in his hippocampal studies, and the duration of stimulation was far less than the 4-day studies of these authors. Coincidentally, with the surface area of the electrodes we use, there is a perfect correlation between the milliamp setting and the number of μC/$cm^2_{(real)}$/phase when a pulse duration of

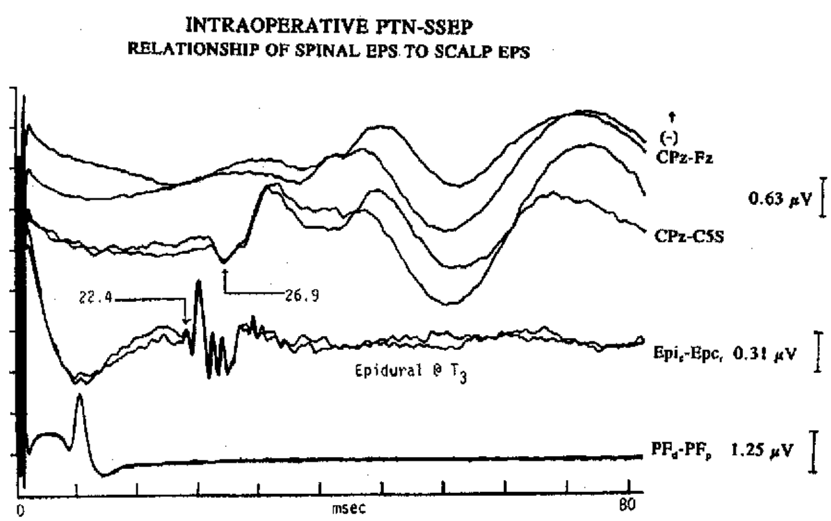


FIG. 7. Two replications of a PTN-SSEP obtained 20 min apart with increasing levels of enflurane. A standard montage with the addition of a bipolar epidural response recorded at the T3 level. Spinal response has onset at 22.4 ms but persists well past the 26.9-ms onset of the P31. Lower-amplitude reproducible components continue past onset of the P37. Of interest is the typical finding of state-independent PF, spinal, P31, and N34 with state-dependent P37, N45, and later components.

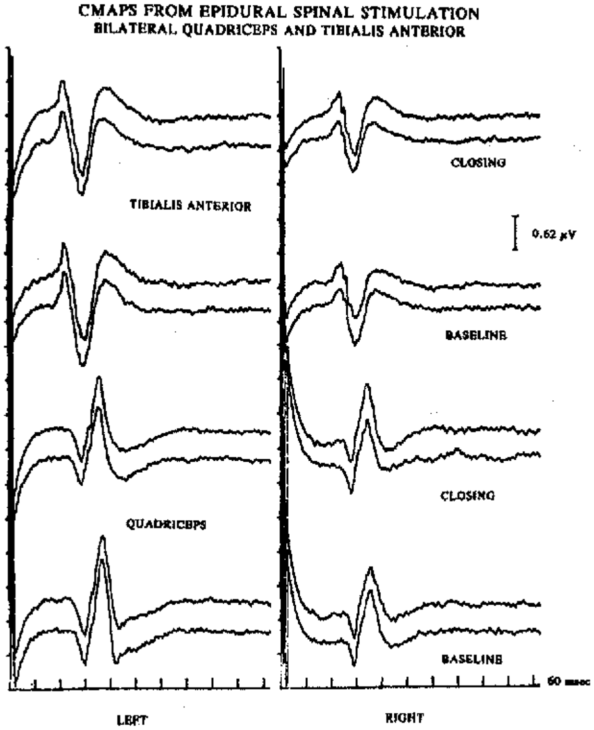


FIG. 8. CMAPs recorded simultaneously from left and right tibialis anterior and quadriceps muscles in response to spinal cord stimulation. Responses obtained at baseline and at closing show no change. Stimulating electrode at T25. Charge density is 13 $\mu C/cm^2_{(real)}$/phase, rate 15.7 Hz, and passband 30–1,500 Hz. At this rate, there is no detected patient movement; paraspinous muscles are in tetany. Enflurane-inhaled concentration was 0.5–1.0%, resulting in low-amplitude CMAPs (see text). Traces are the average of 500 responses.

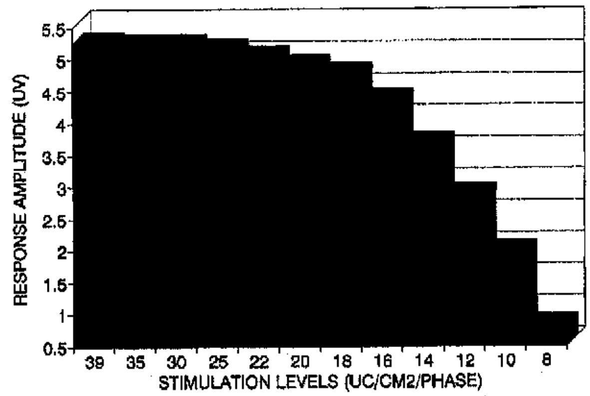


FIG. 9. Input/output characteristics of CMAP amplitudes as altered by different stimulation levels. Over 80% of maximum amplitude reached at 20 $\mu C/cm^2_{(real)}$/phase.

100 μs was used.[1] Thus, when 30 mA is set in the stimulator, the delivered current density is 30 $\mu C/cm^2_{(real)}$/ phase, which is an order of magnitude below the threshold for tissue damage. Figure 9 shows the input/output characteristics of response amplitude of the tibialis anterior motor response to cord stimulation.

CMAPs as large as several thousand microvolts are recorded in response to single stimuli when there are no anesthetic agents present to attenuate the response. Various paralytic agents inhibit the response at the motor endplate level. Succinylcholine not only competitively inhibits the transfer of peripheral acetylcholine but also has central inhibitory effects on the motor synapse in the spinal cord (Cook and Cangiano, 1972). Further, common halogenated inhalational agents block, to varying degrees, motor transmission at the synaptic level in the spinal cord (Zentner et al., 1992). At the minimal alveolar concentration greater than 0.5, electromyographic responses are absent in the rabbit. As a result, one may see CMAPs from various lower limb muscle groups, ranging from several microvolts to several millivolts depending on the anesthetic agents present. One of the clear advantages of spinal motor stimulation is that one can record responses from left and right lower limbs simultaneously and from the quadriceps, tibialis anterior, and other muscle groups as clinically indicated. Because sphincter muscles can also be recorded from, the technique allows assessment of lower spinal anterior roots.

When lower-extremity muscles innervated by lumbar and sacral roots are activated by spinal stimulation, there is also paraspinous muscle activation appropriate to the level of the electrode. Such activation produces a clear movement of the surgical field that can be distracting, at best, to the surgeon. When lower-limb CMAPs are attenuated to the microvolt level due to anesthetic agents, multiple stimuli are required with averaging techniques to extract the response from artifact. Fortunately, motor responses are relatively insensitive to stimulation rates of 15–30/s. At this rate and higher, tetany of paraspinous muscles is produced so that there is no distractive movement of the surgical field. We have

[1] For example, with a constant current of 10 mA and a pulse duration of 100 μs, the total current is 10 mA * 0.1 ms = 1 μC. The surface area of a round electrode is $r^2\pi * 1.4$. The factor of 1.4 adjusts to the true surface area for the microscopically irregular surface of polished platinum. Thus, for the 0.3-diameter electrodes, the surface area is $(0.15)^2 * \pi * 1.4 = 0.10$. The current density per phase is therefore μC/surface area = 1/0.1 = 10 $\mu C/cm^2_{(real)}$/phase. Balanced biphasic stimulation is needed unless the stimulator shorts the outputs after each pulse delivery, which will also prevent current buildup.

used rates to 100/s with no change in amplitude and only minimal changes in latency. Usually, the reciprocal of the sweep time is used to set the rate, which prevents delivery of more than one stimulus during an individual sweep.

CASE ILLUSTRATIONS

Case 1

Figure 10 was obtained during intraoperative monitoring of a 16-year-old girl with an atypical scoliotic curve. An imaging study demonstrated a probable intramedullary thoracic neoplasm. Cytologic confirmation of an intramedullary low-grade glioma was obtained following repeated needle biopsies. The illustration demonstrates spinal recordings from below and above the biopsy site by interlaminal needle electrodes. Repeated biopsies led to progressive attenuation and loss of the spinal response. Cortical and subcortical responses were also obtained before biopsies were taken, and as expected these were also abolished in the process. Immediately upon awakening, the obtunded child was grossly intact to motor and sensory functioning. The next day, the robust cortical and subcortical responses present in the preoperative state remained absent despite normal clinical sensory and motor functioning to extensive examination in an awake, cooperative patient. Six weeks later, the patient returned for instrumentation to arrest her progressive curvature. The decision had been made to discontinue the intramedullary exploration in this asymptomatic patient because of the unpredictablility of the rate of progression of the neoplasm.

The case illustrates the electrophysiologic sensitivity of direct trauma to the dorsal column pathways, and yet, the clinical insensitivity of these pathways when damaged (Greenberg et al., 1987). With more gross surgery of the spine, the dorsal columns may act as a canary in the mine to various iatrogenic disturbances, but in discreet surgery of the spinal cord, major alterations of evoked responses could inappropriately lead to a modification or discontinuance of needed surgery. This observation should not be surprising because clinical experience with multiple sclerosis often shows markedly abnormal electrophysiologic data in patients who are asymptomatic for that particular pathway.

Case 2

Figure 11 demonstrates spinal evoked responses in a patient with progressive spinal stenosis and position-dependent neurogenic claudication. In the early stages of surgery, scalp and scalp-neck responses were obtained that were normal and comparable to the normal preoperative baseline studies. Within several minutes of the placement of an epidural electrode, and prior to any significant surgical

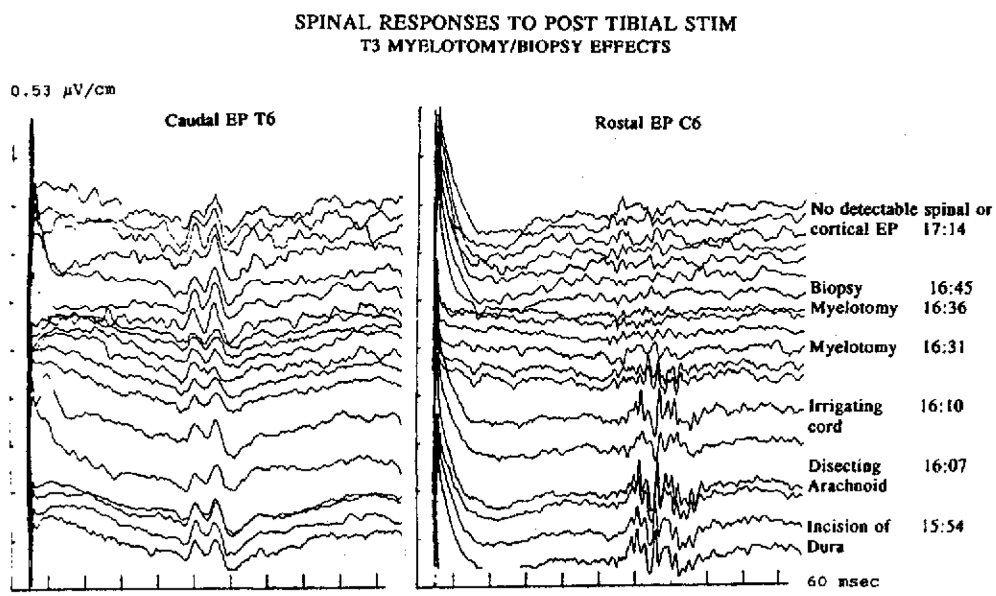


FIG. 10. Referential epidural responses from below (**left**) and above (**right**) an intramedullary neoplastic lesion. Myelotomy and biopsy produced essential loss of responses rostral to the surgical site. See text for discussion.

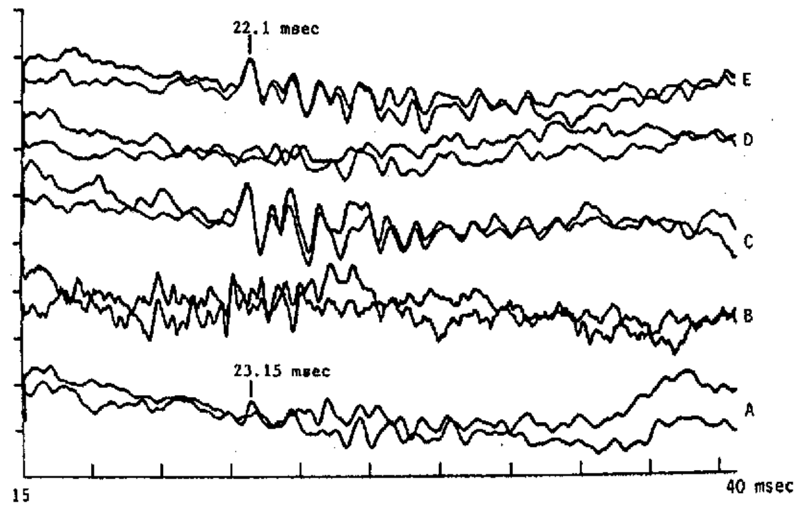


FIG. 11. Bipolar epidural responses to posterior tibial stimulation in a patient with position-dependent neurogenic claudication secondary to spinal stenosis. Loss and return of epidural responses were related to angulation of the surgical table and surgical decompression. See text for further discussion.

manipulation, epidural responses began to attenuate, losing recognizable characteristics (see "A") before adequate spinal epidural baseline responses could be obtained. Scalp derivations confirmed the loss of responses. Unchanged PF responses confirmed the adequacy of stimulation. The spinal actiity further deteriorated to the responses seen in "B." The senior surgeon recalled the presentation of symptoms and asked whether the straight position of the operating table could be compromising cord function (perfusion). Subsequently, the table was angulated to a 15% angle, and the responses seen in "C" were obtained within 3 min. When the table was straightened again to confirm the validity of the correlation, the responses were once again lost as shown in "D." When the table was again angulated, the responses promptly returned as shown in "E." Following decompressive surgery, the table was again straightened, but responses were retained unaltered.

It is conjectural whether this patient would have suffered irreversible neurologic trauma had the table not been bent. However, it was generally felt that the responses correlated well with the patient's symptomatology and subsequently confirmed the adequacy of the decompressive surgery. Following surgery, there was marked relief from the neurologic claudication, which had prompted the surgery.

DISCUSSION AND SUMMARY

We have focused this discussion on a combination of sensory and motor spinal cord monitoring techniques as might be used in typical "spinal" cases. Although the general principles are similar, we have not discussed cervical cord monitoring, which is a more limited topic with some unique technical considerations beyond the scope of this presentation.

The major goals of the techniques discussed were to find methods to provide highly reproducible, unequivocal data with rapid collection by techniques that are refractory to the majority of anesthetic agents. The techniques we have described use standard instrumentation and averaging with routine analog filtering. The filtering selected has been minimal to prevent phase shift.

To accomplish these goals, standard tibial nerve techniques have been applied with recording of the all-important peripheral potentials at the PF, with major emphasis on subcortical brainstem potentials arising from above the site of potential surgical jeopardy. The P31 and N34 components are of far-field origin and recorded in scalp to noncephalic derivations. They are usually lower in amplitude but far more resistant to anesthetic effects than the cortically generated P37. They are robustly present at stimulation rates that obliterate the cortically generated P37. They vary considerably in amplitude such that they may be larger than the P37 in some patients but absent or of extremely low amplitude in some 20–30% of normal subjects.

The spinal evoked potentials, recorded by bipolar electrodes placed in the epidural space, have been used at our institution in over 1,000 cases. High-quality data have been universally present with the exception of those patients with pre-existing severe spinal cord damage or the rare obvious technical error or malfunction. The epidural electrodes can be placed within a 5-min period, and, when properly strain relieved, are resistant to even vigorous surgical manipulations. The major advantages of these potentials are: (1) highly reproducible morphology, (2) nearly total resistance to anesthetic effects, (3) absence of significant artifact, and (4) stability of responses even at high rates of stimulation. Rates to 100/s have been shown to have little effect other than a minimal increase in latency with no significant change in amplitude. The absence of nearby muscle tissue essentially eliminates myogenic artifact. The closely spaced electrodes provide excellent in-phase, common mode rejection. The only anesthetic effects we have observed have followed intravenous bolus injections of narcotics or barbiturates. Such changes are transient and recover within several minutes.

Lower-extremity motor evoked responses are readily obtained following spinal cord stimulation from the same epidural electrode used for recording sensory potentials. CMAPs recorded from quadriceps, tibialis anterior, or other muscle groups, including sphincter muscles, allow for bilateral, simultaneous assessment of spinal cord and root function at varying levels of the lumbar and sacral plexuses. Such motor responses are resistant to rate effects following stimulation at rates of 15–25/s. Such high rates produce tetany of paraspinous muscles and avoid the problems of patient movement during surgery.

Two cases were presented, the first illustrating the high sensitivity of spinal responses to discreet surgery and needle biopsy of the dorsal columns, resulting in loss of response but no associated detectable clinical deficit of either motor or sensory systems. These electrophysiologic alterations persisted for at least 24 h but recovered 6 weeks later. In a second case, spinal responses were demonstrated to be sensitive to position-dependent spinal cord compression secondary to spinal stenosis, which could be manipulated by patient positioning on the operating table. The evoked responses proved useful in confirming the adequacy of the decompression.

This discussion has not been extended to techniques utilized at other centers. The editors requested a description and rationale for the techniques we currently use. Invariably, techniques will vary from center to center, dependent on various factors including the training and experience of the anesthesiologists, the interests and training of the surgeons, and the patient population being evaluated. The authors are well aware of alternate techniques being used by others and encourage the reader to make adaptations appropriate for their own individual needs.

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