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Intraoperative Monitoring of Sensory-evoked Potentials

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CONTENTS

SENSORY-EVOKED POTENTIALS (SEP) are the electrophysiologic responses of the nervous system to sensory stimulation.[1–4] They reflect the functional integrity of specific sensory pathways and serve to some extent as more general indicators of function in adjacent structures. This review will introduce the practicing anesthesiologist to 1) the rationale for intraoperative monitoring of SEP; 2) basic principles of recording SEP; 3) the current state of the art; and 4) the problems and controversies surrounding routine intraoperative use of these electrophysiologic monitoring techniques.

The Rationale for Monitoring SEP Intraoperatively

SEP can provide information about neurologic function during anesthesia and operation that would otherwise be available only through clinical assessment of the unanesthetized patient. For example, electrical potentials elicited by electrical stimulation of a sensory or mixed nerve in the leg and reproducibly recorded from the scalp during an operation on the spine or spinal cord indicate preservation of sensory transmission through the cord.[5–7]

Conceptually, recording of SEP may be valuable whenever pathways amenable to SEP monitoring are at risk. Several workers have monitored SEP during neurosurgical, orthopedic, and vascular operations, attempting to reduce the incidence of neurologic injury associated with these procedures. The largest collective experience is with monitoring of somatosensory-evoked potentials (SSEP, fig. 1)[3] during operations on the spine or spinal cord. Brain stem auditory-evoked potentials (BAEP, fig. 2)[8,9] are recorded during neurosurgical procedures in the posterior cranial fossa,[10] and visual-evoked potentials (VEP, fig. 3)[11] during operations impinging on the optic nerve or chiasm. The hope is that deteriorating neurologic function will be detected early, so that the surgeon and/or anesthesiologist can intervene to optimize function and minimize the possibility of permanent damage to the nervous system.

Basic Principles of Recording SEP

Evoked potentials, often of lesser voltage than the spontaneous electroencephalogram (EEG), are made apparent by summation or averaging of multiple EEG segments precisely time-locked to repetitive sensory stimulation.[3,12] Because EEG activity is to some extent random, the ratio of SEP "signal" to EEG "noise" increases as the square root of the number of repetitions in an average. The averaged SEP, like the EEG, is displayed most often as a plot of voltage against time (fig. 1). It is customarily described in terms of the post-stimulus latencies (in milliseconds) and peak-to-peak amplitudes (in microvolts or nanovolts) of individual peaks in the waveform.[13]

Neural generators of individual SEP peaks have been postulated on the basis of clinical studies in humans,[14–16] clinical-pathologic correlations,[17–19] studies in animals,[20,21] and intraoperative recordings from neural structures in humans.[22–25] Although these neural

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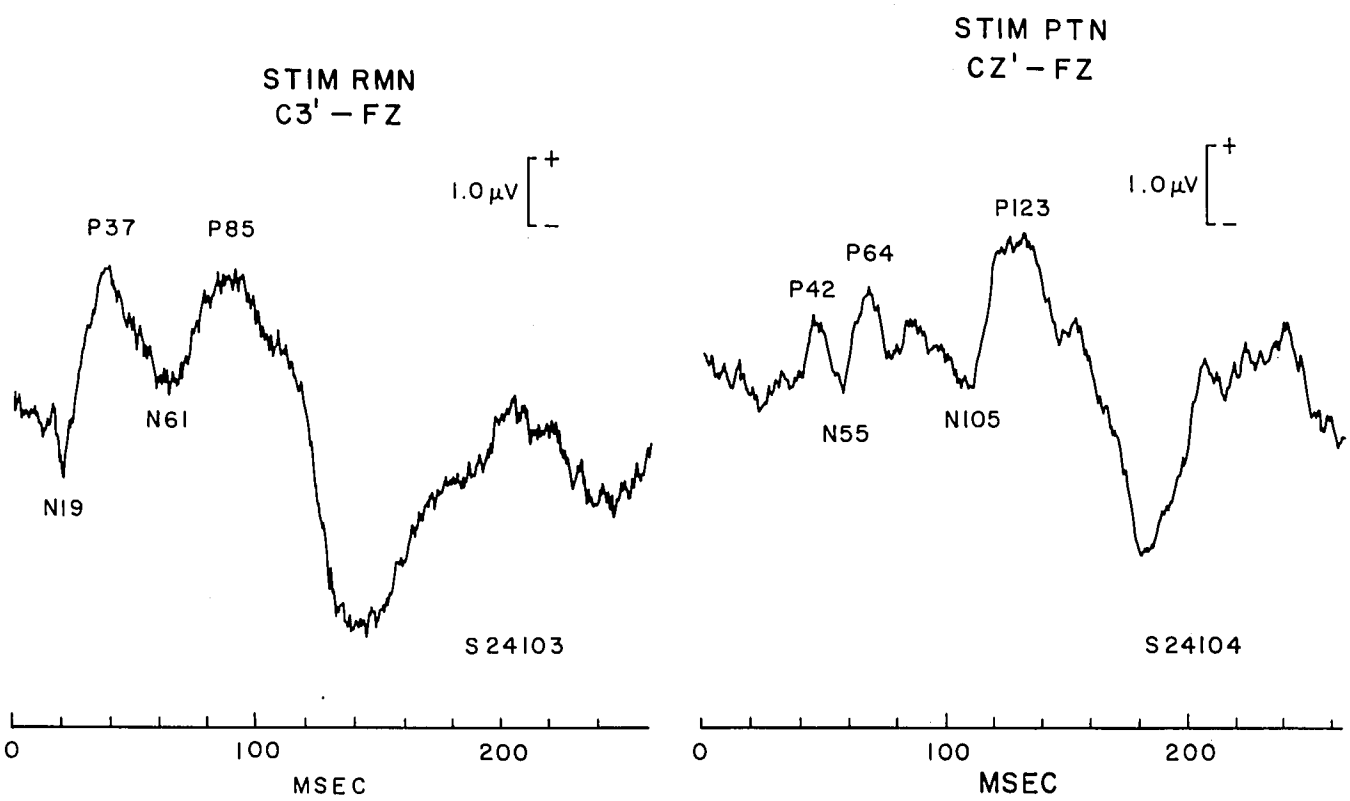

FIG. 1. Normal somatosensory-evoked potentials recorded in the operating room prior to induction of anesthesia, using the parameters shown in table 1. The patient was to have suboccipital and cervical decompression for Arnold Chiari malformation and had been premedicated with meperidine, hydroxyzine, and atropine. Waveforms were reproducible, but later components were probably affected by the premedication. (*A*) Response to stimulation of the median nerve at the wrist. (*B*) Response to stimulation of the posterior tibial nerve at the ankle. The artifact seen in the unretouched waveform does not interfere with interpretation. The peaks labeled P for postive or N for negative, with numbers designating post-stimulus latency,[13] are thought to arise in the primary somatosensory cortex. Preceding unlabeled negative waves, approximately 14 ms after stimulation of the median nerve at the wrist and 30 ms after stimulation of the posterior tibial at the ankle, probably arise in the dorsal column nuclei. The somatosensory central conduction time after median nerve stimulation, determined by subtracting the nominal N14 from the nominal N20, is a sensitive indicator of cerebral ischemia.[30,32] Early negative waves are less well-defined in responses to stimulation of nerves in the lower extremities. Post-stimulus latencies of early negative peaks show less interindividual variability and are less affected by anesthetics than later waves. These tracings demonstrate the normal interindividual variability of the so-called "primary specific complex", a V- or W-shaped wave nominally P25, N40, P50, N65, P90 after stimulation of the median nerve at the wrist, and approximately 15 ms later after stimulation of the posterior tibial nerve at the ankle. Specifically, the P25-N40-P50 complex, seen well in figure 8, is replaced here by a postive wave 37 ms after stimulation. The explanation for such interindividual variation is not known; when each subject serves as his own control, this interindividual variability does not interfere with monitoring.

generators have not been definitely proven, the designations are clinically useful (figs. 1–3). Loss of sensory transmission demonstrated by obliteration of the SEP past a particular peak, or slowed conduction shown by abnormally increased peak latencies,[26,27] can help localize not only tumors and other structural lesions of the nervous system[18,28] but also areas of ischemia,[29–32] infarction,[17] or demyelination.[33] SSEP are used to evaluate patients with injuries of the spinal cord.[34] Multimodality SEP provide information of diagnostic and prognostic importance in comatose patients.[35–38] Electrodiagnostic studies of brain death may include SEP recordings,[39,40] and BAEP are used to screen newborns for deafness.[41] Because latency and amplitude values vary with changes in recording techniques, normal values must be established within each laboratory.[42]

Systems for recording evoked potentials include several components: 1) devices that provide sensory stimulation; 2) transducers for applying stimuli to the patient; 3) electrodes for detecting neurophysiologic signals generated by the patient; 4) filters and amplifiers to condition the recorded signals; 5) a computer to control stimulation and signal acquisition, to sum or average the acquired signals, and to measure latencies and amplitudes of peaks in the averaged wave forms; 6) programs for the computer; and 7) devices for display and storage of SEP. Several commercially available systems are sufficiently versatile to record a variety of SEP using

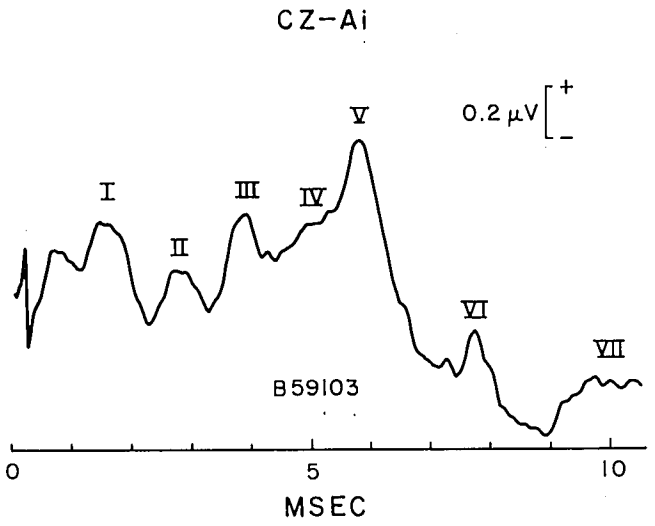

FIG. 2. Normal brain stem auditory-evoked potential, recorded from the vertex (CZ) to the earlobe ipsilateral to auditory stimulation (Ai). Purported generators of labeled peaks are: I—extracranial portion of auditory nerve; II—intracranial portion of auditory nerve and/or cochlear nucleus; III—superior olive; IV—lateral lemniscus; V—inferior colliculus; VI—medial geniculate; and VII—thalamocortical radiations.

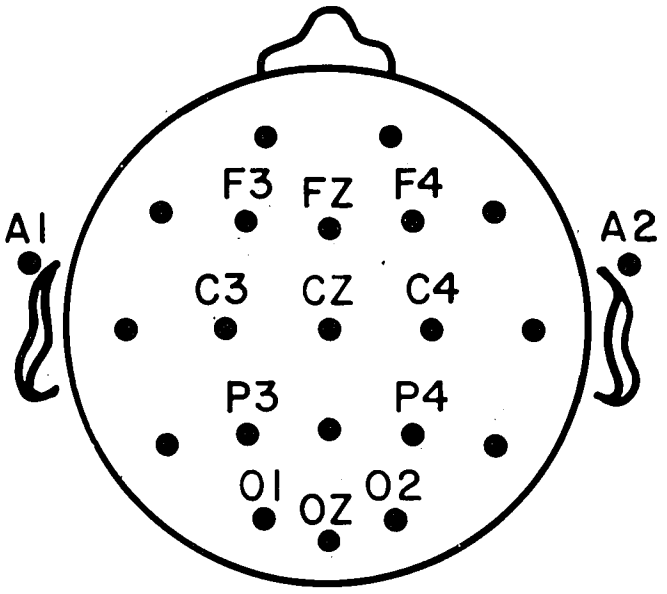

FIG. 4. Electrode locations designated by the International Ten Twenty System.[138] These positions are based on measurements of head circumferance, interaural distance, and the distance from nasion to inion.

push-button controls and ready-to-use computer programs. Alternatively, general purpose computers can be used and programs can be developed locally. As a rule, the costs of program development far exceed the costs of computer hardware.

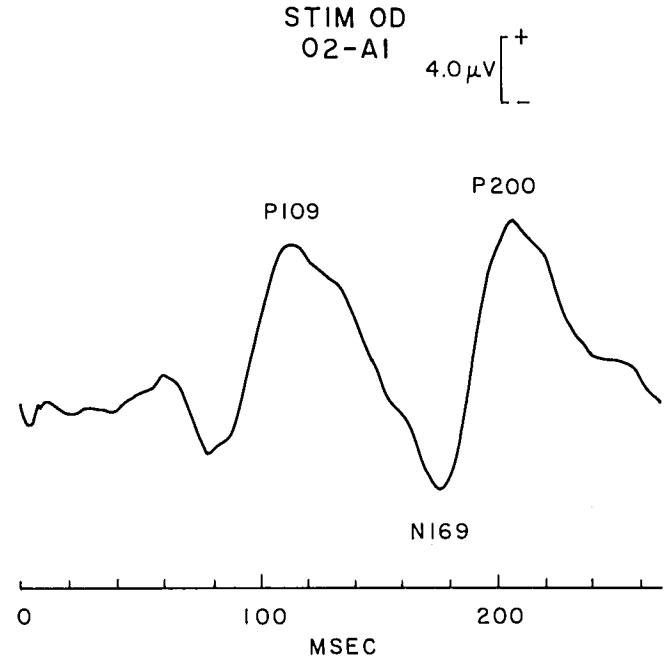

FIG. 3. Normal visual-evoked potential elicited by flash stimulation over closed eyelids. The nominal P100, here 109 ms after stimulation, arises in the occipital cortex and is the most important marker for intraoperative monitoring.

SEP elicited by somatosensory, auditory, and visual stimulation are monitored intraoperatively. Activity arising in the cerebral cortex, subcortical structures, cranial nerve, spinal cord, nerve root, plexus, and even peripheral nerve can be recorded noninvasively from electrodes fixed to skin or scalp.[43,44] During operation, electrodes can be placed within the surgical field. Locations of electrodes (fig. 4) and parameters used for stimulation and recording (Table 1) vary according to several factors: the modality of sensory stimulation; the neural generators of interest; the component frequencies in the SEP waveforms, and distances between neural generators and recording electrodes.

SEP recorded from electrodes near their neural generators are called "near-field" potentials. For example, cortical SEP recorded from scalp electrodes[14] or spinal SEP recorded from electrodes in bone, intraspinous ligaments,[45] or the spinal epidural space[46] are near-field SEP. "Far-field" potentials (*e.g.*, potentials arising in peripheral nerve, spinal cord, or subcortical structures and recorded from scalp electrodes) are smaller in amplitude than near-field potentials. Signal strength falls as the distance from neural origin to recording electrode increases, and averaged responses to several thousand repetitions of the sensory stimulus may be needed to demonstrate far-field evoked potentials.

Adequate quality control in recording SEP demands the full attention of an experienced technician. Because the neurophysiologic signals are small, while noise from both mechanical and electrical sources abounds in the

TABLE 1. Parameters Used for Intraoperative Recording of SEP*

	SSEP	BAEP	VEP
Stimulus	Electrical current	Filtered clicks	Flash over closed eyelids
Transducer	Subdermal platinum electrodes	Ear insert	Goggle-mounted light-emitting diodes
Duration	250 μs	100 μs	5 ms
Rate	0.9–1.9 Hz	11.2 Hz	0.9–1.9 Hz
Intensity	2–20 mAmp	60 dB above patient's hearing threshold	Affected by eyelid thickness; not measurable or adjustable
Recording			
Channels	2 cm behind C3-FZ†	CZ–A1	OZ–A2
	2 cm behind C4–FZ	CZ–A2	PZ–A2
	2 cm behind CZ–FZ		5 cm left of OZ–A2
	Skin over second cervical vertebra or Erb's point-FZ		5 cm right of OZ-A1
Ground (patient's reference)	Sternum	FZ	A1 or A2
Filters	1–1500 Hz	30–3,000 Hz	1–1,500 Hz
Repetitions per average	128	2,000	128
Common amplitude standardization	5 μV	0.5 μV	5 μV
Duration recorded	256 ms	10.24 ms	256 ms

* These are the parameters employed by the Division of Neuroanesthesiology at the University of Pittsburgh using a Nicolet MED 80 Biomedical Data System (Nicolet Biomedical, Inc., Madison, Wisconsin). Other systems and parameters can be used successfully.

† Electrode positions as designated by the International Ten Twenty System.[138] Odd numbers are on the left, even numbers on the right. C3 and C4 are over the primary sensory hand areas, CZ is at the vertex, and A1 and A2 are the earlobes.

operating room environment, meticulous technique is mandatory. Alterations in stimulus[47–49] and recording[50] parameters can modify elicited waveforms,[49] so that technique should be kept constant during each monitoring session. A physician experienced in intraoperative monitoring of SEP, whether neurologist, neurosurgeon, or anesthesiologist, must be available to interpret the wave forms acquired during anesthesia and operation.

The State of the Art

The clinical applicability of SEP recording in the operating room will ultimately depend on the feasibility, sensitvity, utility, and reliability of these electrophysiologic monitoring techniques. Recent reports provide information about the present value of SEP for intraoperative assessment of neurologic function, based on these four criteria.

FEASIBILITY

The feasibility of intraoperative electrophysiologic monitoring can be assessed by examining the availability and costs of equipment and personnel, the time required for SEP monitoring in a busy operating room, the frequency with which technical difficulties disrupt monitoring, and the constraints that may be placed on anesthetic management to facilitate monitoring of SEP.

Equipment for monitoring SEP may cost $20,000 to $90,000, and personnel costs are not inconsiderable when the full attention of a technician is required for several hours. Costs and time requirements are not discussed in most reports, but certain trade-offs are immediately apparent. For example, some investigators hold the opinion that baseline SEP should be recorded prior to induction of anesthesia on the day of operation, then continually during anesthesia and operation. Others institute monitoring only after the patient is anesthetized and positioned. Systematic analyses describing the cost-effectiveness of various maneuvers carried out in the name of quality control are lacking.

Most of the investigators who have monitored SEP during anesthesia and operation have encountered technical difficulties in some degree. Signal acquisition is difficult. Equipment is complex. Few technicians and physicians are experienced in recording and interpreting SEP intraoperatively. Despite these difficulties, teams willing to take precautions, that are at present somewhat cumbersome, can use these monitoring techniques effectively.

Several factors under the control of the anesthesiologist can affect SEP. These include anesthetic agents[51–56] and other drugs that act on the nervous system,[57–60] temperature,[61–63] arterial blood pressure,[64–66] tensions of respiratory gases,[67–70] and hematocrit.[71] SEP can vary even with the stages of natural sleep.[72,73] Subcortical potentials, including those that arise in spinal cord or peripheral nerve, are less sensitive than potentials of cortical origin to anesthetics,[74] ischemia,[75,76] and hypoxia,[68,70] even though tensions of respiratory gases are known to affect spinal cord blood flow in dogs.[77] Halogenated agents generally are avoided when cortical potentials are to be monitored,[78] but subcortical SEP can be monitored with virtually any anesthetic technique.[10,74,79] Late cortical potentials are too variable to be useful intraoperatively.

If SEP are to reflect the effects of surgical trespass, potentially confounding variables must be monitored and kept relatively constant. After each pharmacologic or physiologic intervention (*e.g.*, induction of anesthesia, deliberate hypotension,[80,81] or hypothermia[63]), a new steady state is established and new "reference" SEP are recorded for subsequent comparison with wave forms obtained during critical operative manipulations. Bolus injections of anesthetic agents that can affect SEP should be avoided during critical monitoring periods. Constant infusions of some intravenous agents may be appropriate.[82] Successful intraoperative monitoring of SEP thus requires the active collaboration of the anesthesiologist, no matter who assumes primary responsibility for recording and interpreting waveforms.

Both Raudzens[83] and Allen *et al.*[84] found *SSEP* the most technically difficult evoked potentials for intraoperative monitoring. Six of Raudzens' 31 patients had technically inadequate waveforms. Allen and his colleagues obtained technically satisfactory SSEP in only 12 of 21 patients. Engler and Spielholz,[78] on the other hand, reported technically adequate recordings in 54 of 55 cases. Nash and Brown, using a recording system specifically designed for intraoperative monitoring of cortical SSEP,[6,66,85,86] have successfully monitored somatosensory function during more than 500 orthopedic and neurosurgical procedures (Brown RH: personal communication). Problems in obtaining satisfactory SSEP may be related to technical difficulties in achieving adequate stimulation of sensory nerves, to the lack of general agreement on optimal locations for recording electrodes, and to effects of anesthetics on cortical potentials.

BAEP are recorded and interpreted more easily than are the potentials elicited by stimulation in other sensory modalities. Fewer electrodes are required, and electrode placement is simpler for BAEP than for SSEP. Allen *et al.*[84] obtained satisfactory waveforms in nine of ten cases, and Raudzens[83] in all of 66 cases. Investigators at Children's Hospital, University Health Center of Pittsburgh, lost BAEP intraoperatively in two of their ten patients—once due to technical difficulties and once without apparent cause (Bursick DM, McKeever R, Vries JK, Sclabassi RJ: unpublished).

We obtained technically adequate BAEP in all of 54 cases,[10] but signals were lost due to technical problems during three operations early in the series. Fortunately, the technical problems were appreciated in each instance, so that inappropriate interventions based on false warnings of BAEP obliteration were avoided.

Technical difficulties with recording of BAEP are unlikely to stem from effects of anesthetics. Subcortical potentials may be altered slightly by these agents, but monitoring still can be performed. Displacement or disconnection of stimulators, impaired transmission of sound due to compression of pliable earpieces, or loss of inaccessible electrodes can interfere with monitoring of BAEP. In the presence of conductive or sensorineural hearing loss, BAEP are absent even though the brainstem may be normal. Attention to detail can minimize technical difficulties, and preoperative recording of audiograms and BAEP will identify those patients in whom deafness precludes intraoperative monitoring of BAEP.

VEP were used for intraoperative monitoring as early as 1973,[87] but several technical problems continue to limit their usefulness. First, only flash stimulation is feasible during most operations,[88] and flash-evoked potentials[89] are less well-defined and less reproducible than the pattern-reversal-evoked potentials commonly employed in the diagnostic laboratory.[11] Second, the devices available for intraoperative visual stimulation, light-emitting diodes mounted in opaque goggles, are not appropriate for all applications. A sterilizable, flexible, low-profile device is needed for safe and reliable flash stimulation through closed eyelids during surgical procedures in the anterior cranial fossa. Finally, the most appropriate stimulus rates, electrode locations, and filter settings for intraoperative recording of VEP have not been defined fully.

Allen *et al.*[84] obtained sastisfactory VEP in 22 of 25 patients. Raudzens,[83] in 71 cases, found that VEP were excessively variable during anesthesia and operation. Anesthetic management and technical problems may have contributed to the difficulties with intraoperative monitoring of VEP that were encountered by Allen and Raudzens. Cortical VEP are quite sensitive to anesthetics.[51,53,55] Far-field subcortical VEP[90] have received little attention and have not yet been recorded during anesthesia and operation.

In summary, intraoperative monitoring of SEP is feasible, if somewhat cumbersome and expensive. Improvements in the presently available methods can be expected as experience accumulates and as equipment and techniques more responsive to clinical needs are developed.

Sensitivity

Although direct cause-and-effect relationships are less easily demonstrated in the clinical setting than in the animal laboratory, the frequency with which SEP changes are seen and the association of SEP alterations with intraoperative events of interest reflect the sensitivity of SEP as intraoperative monitors of neurologic function.

Intraoperative changes in SEP may be related to ischemia,[32,91] distortion,[92] or disruption[10] of neural structures. Studies in animals have shown that hypotension

contributes to the changes in SSEP produced by direct pressure on the spinal cord[64,93] or cerebral cortex,[94] and patients' SEP may deteriorate when arterial blood pressure falls during neurosurgical or orthopedic operations.[66,95] Transection of a sensory pathway (*e.g.*, the auditory nerve) is, of course, followed by loss of both function (*e.g.*, hearing) and the related evoked potential (*e.g*, the BAEP produced by stimulation of the affected ear).

Operative manipulation of neural or vascular structures can alter SEP, as can pressure on neural structures from surgical retractors.[96] For example, SSEP may be affected by manipulation of a spinal cord tumor[97] or by obliteration of vessels feeding an arteriovenous malformation of the cord (fig 5).[98] Similarly, instrumentation of the vertebral column or a change in the position of an unstable spine can alter somatosensory transmission, often while functional changes are still reversible.[6,78,99]

In patients with preexisting pathologic processes in the posterior fossa, changes in BAEP have been observed after induction of anesthesia but prior to surgical incision. These alterations were in some cases associated with the combination of hypocarbia and modest hypotension,[10] in others with positioning of the head and neck for retromastoid craniectomy.[100] Perhaps ischemic mechanisms were involved.

Cortical SEP are sensitive indicators of some systemic problems that may threaten the viability of the brain during anesthesia, such as hypoxia,[68,69] excessive hypotension,[101] or overdose of anesthetic.[55] They have not been compared to multichannel EEG for monitoring brain function during carotid endarterectomy[102–104] or to compressed EEG for monitoring during coma or hypotension.[105]

Intraoperative changes in SEP occur with a frequency that exceeds the anticipated frequency of neurologic injury in unmonitored patients. Moreover, most intraoperative SEP alterations are reversible.[10,83,84,95,97] Thus, SEP seem sufficiently sensitive as indicators of compromised neurologic function that early warning of deterioration may often allow intervention to prevent permanent damage.

Utility

Monitors may be considered useful when they provide information that aids clinical descision making or prompts therapeutic intervention. The interventions based on intraoperative deterioration of SEP are most often surgical,[6] but intervention by the anesthesiologist is not infrequent.[10,68,95] In some cases, the surgeon may proceed in the face of substantial risk so long as stable SEP indicate intact function. In other instances, SEP can facilitate an operative procedure by localizing

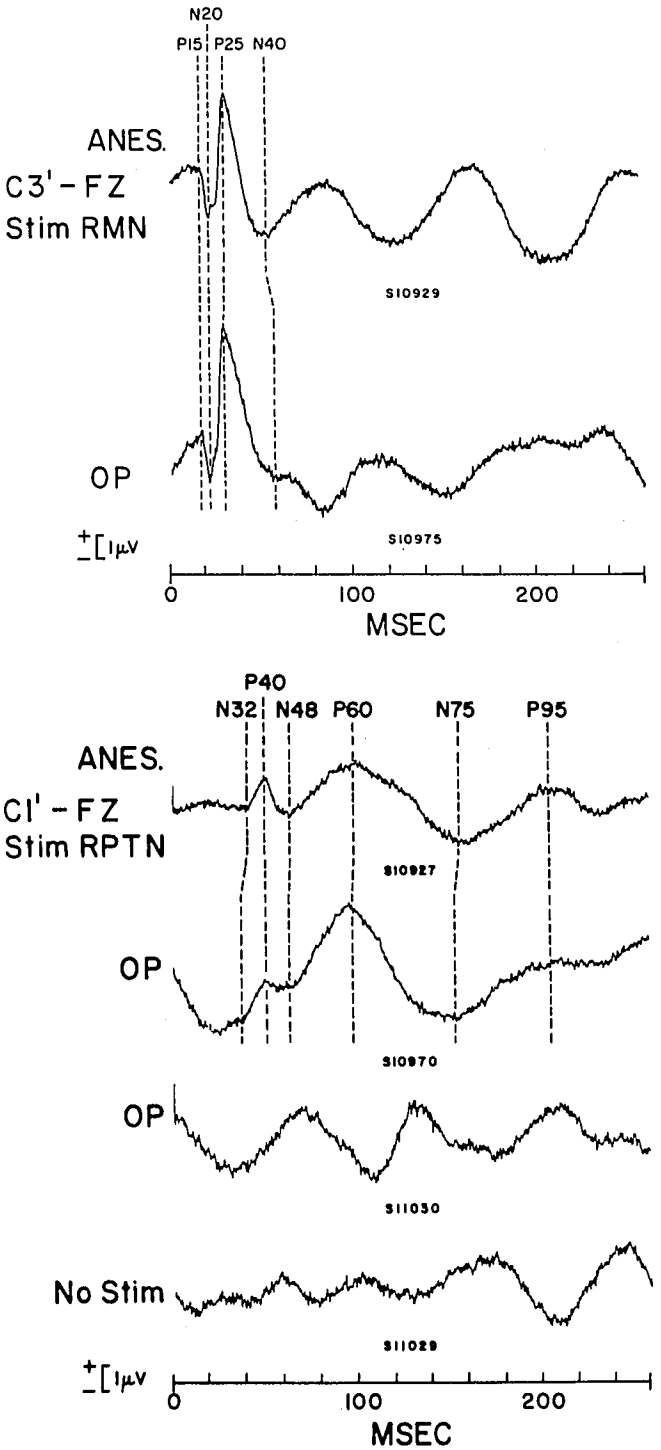

FIG. 5. SSEP recorded during resection of a large arteriovenous malformation of the spinal cord. Responses to stimulation of the median nerve at the wrist remained stable (*A*), while potentials elicited by stimulation of the posterior tibial nerve at the ankle were progressively obliterated (*B*). The patient suffered a permanent cord injury. To facilitate identification of corresponding peaks in successive waveforms, peaks are labeled with nominal normal values for post-stimulus latencies rather than with the actual post-stimulus latencies seen in these tracings. (From Reference 98. Courtesy of the American Society of Anesthesiologists, Inc.)

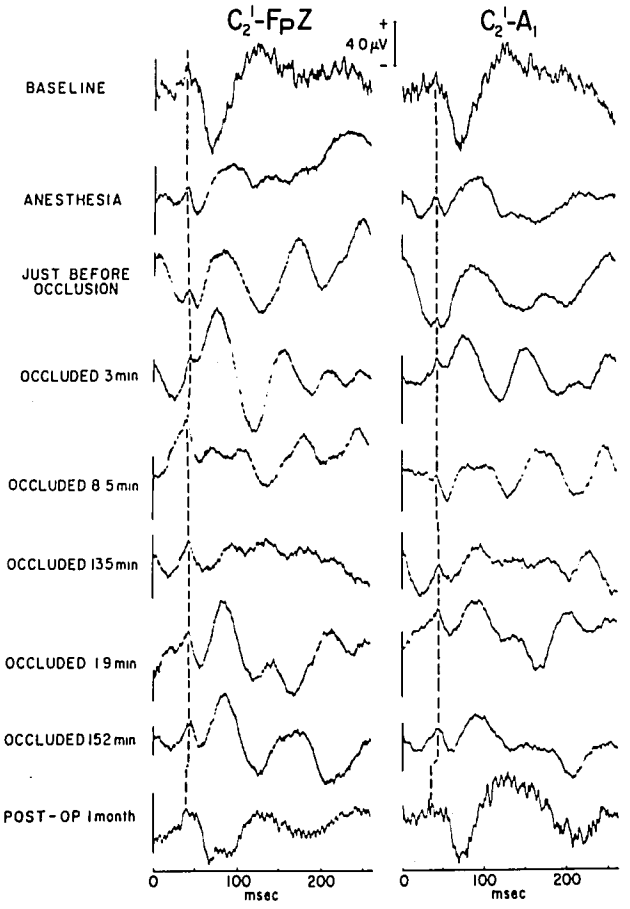

FIG. 6. Somatosensory-evoked potential recorded during resection of an intracranial arteriovenous malformation. SSEP elicited by stimulation of the left posterior tibial nerve at the ankle were recorded during test occlusion of the right anterior cerebral artery to help determine the safety of sacrificing this vessel. The initial cortical positivity, nominally N40, remained stable throughout. Later waves were transiently altered after occlusion of the artery. (From Reference 112. Courtesy of the Congress of Neurological Surgeons, Inc.)

neural structures such as particular branches of an injured brachial plexus,[27,106,107] the sensorimotor strip of the cerebral cortex,[22,25] or deep brain structures that are approached using sterotactic techniques.[108]

During operations on the spine, the surgeon may respond to deteriorating SSEP by lessening the straightening of a spinal curvature[109,110] or by repositioning or removing a bone graft, methylmethacrylate, Harrington rods, or other instrumentation used to stabilize the spinal column.[6,83] The anesthesiologist may raise the arterial blood pressure[111] or reverse hemodilution.[95] When the cervical spine is unstable, alterations in SSEP may resolve upon repositioning of the head and neck. The neurosurgeon performing an operation within the spinal canal may reposition a retractor, approach a tumor from a different aspect, temporarily suspend operative manipulation, or even determine that a lesion cannot be safely resected.[97]

We used cortical SSEP to assess the safety of sacrificing the right anterior cerebral artery, the major feeding vessel of a large arteriovenous malformation (AVM) lying on the corpus callosum.[112] After the initial cortical activity elicited by stimulation of the left posterior tibial nerve was shown to be stable during test occulsion of this vessel (fig. 6), the risk of infarcting the sensorimotor strip was considered to be minimal and the artery was divided. The AVM was completely resected and the patient suffered no neurologic injury.

Intraoperative deterioration of SEP is not always reversible. In eight of the operations monitored by McCallum and Bennett,[113] SSEP amplitudes decreased intraoperatively. Seven of the eight patients had diminished neurologic function postoperatively. SSEP waveforms were stable or improved during seven of 15 operations monitored by the Division of Neuroanesthesiology at the University of Pittsburgh.[97] During seven other procedures, deteriorating SSEP recovered after specific interventions. In one case, however, no intervention was possible. A large AVM on the dorsal aspect of the thoracolumbar spinal cord had multiple small feeding vessels, with no dominant vessels suitable for test occlusion. As the multiple vessels were sacrificed, SSEP gradually but progressively deteriorated. After several hours of operation, SSEP were obliterated completely (fig. 5). The vascular supply of the cord could not be reestablished, and this patient suffered major neurologic injury.[98]

Potentials elicited by stimulation of the trigeminal nerve[114] can be monitored during operations in the posterior fossa. Sweet *et al.* used trigeminal-root-evoked potentials to monitor the results of lidocaine diagnostic block or differential radiofrequency thermal rhizotomy in the treatment of trigeminal neuralgia.[115]

Interventions made on the basis of intraoperative changes in BAEP in our series included repositioning or removal of surgical retractors (fig. 7),[96] temporary cessation of operative manipulation, and raising arterial blood pressure or arterial tension of carbon dioxide.[10] Interventions were made specifically on the basis of BAEP alterations during 22 of 54 neurosurgical operations in the cerebellopontine angle. Recovery of BAEP was seen after the intervention in 19 cases. In the other three of these 22 cases, recovery did not occur before the auditory nerve was sacrificed deliberately.

Raudzens reported interventions based on deterioration of VEP during operations on aneurysms in the anterior cranial fossa.[83] Arterial blood pressure was raised, retractors on the optic chiasm were repositioned, and VEP recovered. We have seen intraoperative improvement in VEP after resection of a large pituitary

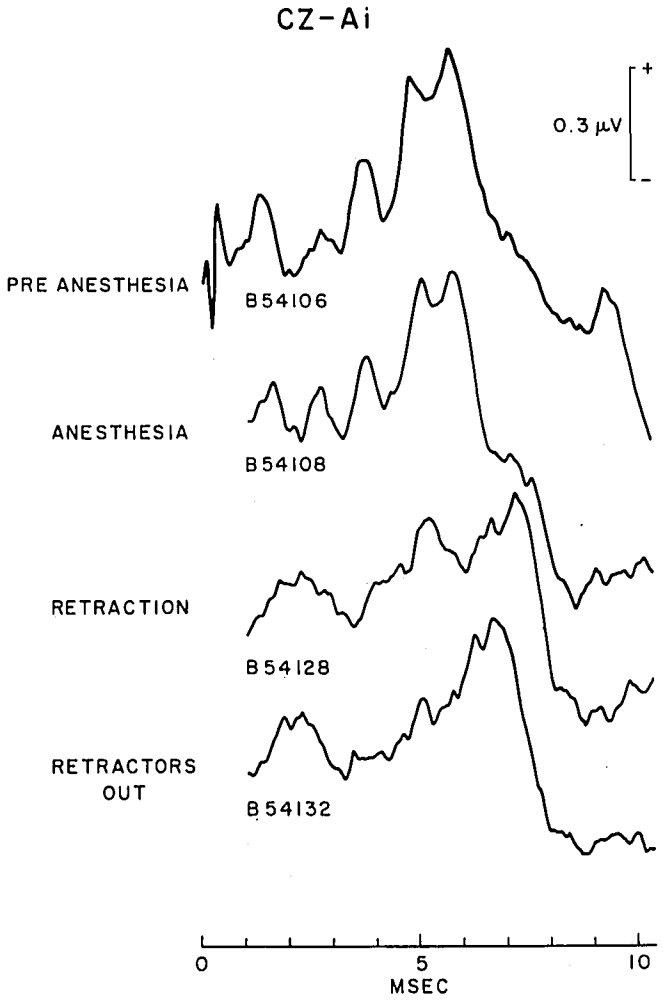

FIG. 7. Brain stem auditory-evoked potential changes associated with retraction of the eighth cranial nerve and cerebellum. Changes in the BAEP were reversible and hearing was preserved. A post-stimulus delay of 1 ms was introduced after induction of anesthesia to eliminate stimulus artifact.

tumor, associated with postoperative improvement in visual function (fig. 8).

The utility of intraoperative electrophysiologic monitoring in selected cases is high. Changes in SEP are often readily apparent while alterations in function are still reversible.

RELIABILITY

The relationship between intraoperative evoked potential findings and postoperative outcomes provides an index of the reliability with which SEP monitoring reflects neurologic function during anesthesia and operation. This index of reliability varies from one reported clinical series to another. Within some series, reliability varies according to the sensory modality monitored.

Technical problems in dynamic situations and confounding factors that affect SEP can cloud the monitoring picture. Further, safe tolerance limits for SEP changes short of obliteration have not been described. Even virtual obliteration of SEP may be compatible with preservation of function provided the changes in SEP are reversible.[68,96,100] The duration of waveform obliteration compatible with recovery of SEP and clinical neurologic function, however, is not known.

Despite these difficulties, intraoperative SEP findings have correlated reasonably well with postoperative neurologic function in several settings. In our experience with 24 orthopedic and 87 neurosurgical cases, SEP at the conclusion of anesthesia have always correctly predicted the presence or absence of postoperative function in the monitored pathway.

Somatosensory-evoked potentials. Raudzens[83] and Allen *et al.*[84] saw only stable or transiently altered SSEP intraoperatively. None of their successfully monitored patients had new neurologic deficits.

McCallum and Bennett[113] saw waveform changes during nine of the 14 operations they monitored. In one patient whose SSEP amplitudes increased during exploration of the spinal cord, the preoperative neurologic deficit was improved after surgery. Of the five patients in whom SSEP were stable, four had no postoperative change in neurologic function. The fifth, who had a Gardner procedure for syringomyelia, suffered an increased neurologic deficit unheralded by intra-

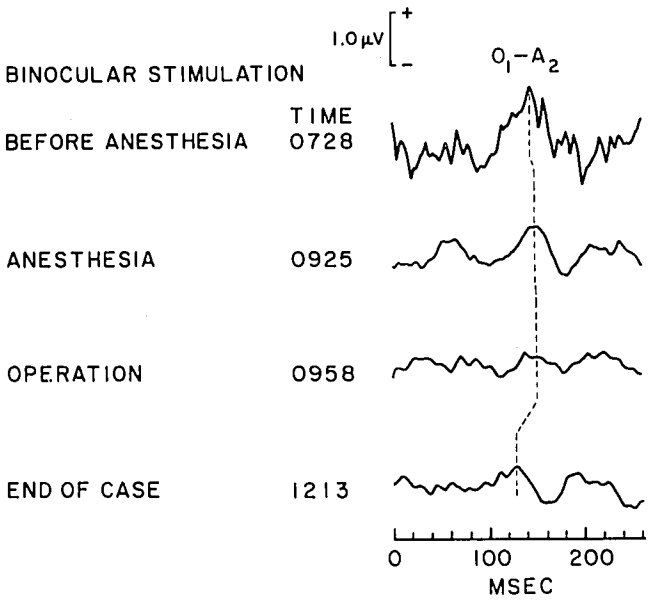

FIG. 8. Visual-evoked potentials recorded during transphenoidal resection of a pituitary tumor. Transient deterioration of the VEP was followed by recovery, with a shorter post-stimulus latency of the nominal P100 than that seen prior to resection of the tumor. The patient's visual function was improved after operation.

operative deterioration in SSEP. Seven of the eight patients with intraoperative decreases in amplitudes of SSEP had diminished cord function postoperatively, but one had no change from his preoperative neurologic status. Thus, intraoperative SSEP in this series correctly predicted postoperative function (unchanged, improved or worsened) in 12 of 14 cases.

Spielholz *et al.*[116] reported improvement in SSEP upon surgical decompression of injured spinal cords in ten patients, and nine of these showed clinical improvement after operation. In a separate and apparently conflicting report,[117] however, these authors described increases in SSEP amplitudes during only three of 11 operative decompressions for acute spinal cord injury. One patient with markedly improved SSEP during operation never regained motor function or pain perception. Of the 11 patients described, eight subsequently had improved neurologic function and three did not. In this paper,[117] Spielholz *et al.* concluded that clinical outcome of operative treatment for acute injury of the cord was not related to whether SSEP improved or remained the same during surgery. Still, no patient who maintained SSEP intraoperatively lost function after surgery; and the presence of an SSEP during operation was usually, but not always, associated with some degree of clinical recovery.

Engler *et al.*[78] monitored SSEP during 54 operations for correction of scoliosis with Harrington rod instrumentation. Minimal latency and amplitude changes were seen after straightening of the spine in most of their patients, but SSEP were preserved in all, and none suffered neurologic injury.

Brown and Nash[118] at Case Western Reserve University have monitored cortical SSEP during more than 500 orthopedic and neurosurgical operations (Brown RH: personal communication). In their experience, intraoperative SSEP have correlated well with postoperative neurologic findings.

Cortical SSEP were monitored by the Division of Neuroanesthesiology at the University of Pittsburgh during 15 neurosurgical operations.[97] In each case, SSEP at the end of anesthesia correctly predicted postoperative somatosensory function, and there were no instances of dissociated motor loss when SSEP were intact. The single patient who had irreversible intraoperative obliteration of SSEP suffered major deficits in both sensory and motor function.[98]

In a study of induced hypotension during spine fusion for scoliosis, we monitored spinal cord function using cortical SSEP.[95] For decreases of 50% or more in SSEP amplitudes, or for latency increases of more than three milliseconds that persisted after reversal of hemodilution and, if present, hypotension, we performed a "wake-up test."[119] Wake-up tests were performed in five of the 24 patients studied. In each case, voluntary motor function was found to be intact and SSEP alterations resolved intraoperatively. There were no neurologic deficits postoperatively.

SSEP can be monitored continually during anesthesia and operation, whereas wake-up tests can be used only at infrequent intervals. Furthermore, SSEP monitoring, like electrocardiographic monitoring, introduces little risk of injury. The wake-up test, in contrast, may be associated with risks of air embolism; displacement of monitoring or life support devices; dislodgement or orthopedic instrumentation; or psychologic trauma. Our findings suggest that SSEP are sufficiently sensitive as indicators of impaired spinal cord function during posterior spinal fusion that wake-up tests can be safely omitted so long as SSEP are monitored and remain stable. Because hypotension and direct pressure on the cord are additive in their adverse effects on cord function,[64] monitoring of SSEP seems particularly useful when hypotension is deliberately induced during operations on the spine or spinal cord.

Spielholz *et al.*[117] stressed the need for a sensitive electrophysiologic monitor of anterior cord function. It is surprising that intraoperative changes in cord function seem to be globally reflected in SSEP, which are transmitted primarily by the dorsal columns. Perhaps blood flow to the entire cross-sectional area of the cord is at least transiently altered by operative insults to the cord or its blood supply. There is no doubt that stable lesions of the anterior cord may be associated with complete motor loss while SSEP are preserved.[120]

The reliability of SSEP for monitoring spinal cord function during operations on the aorta has not been tested. In the report by Szilagyi *et al.*[121] of 44 cord injuries following aortic surgery, 36 from the literature and eight from their own experience, 15 patients had intact proprioception, and three had unspecified "partial" sensory function. The patients with clinically intact function of the dorsal columns would, in all likelihood, have had normal SSEP. One can only speculate about the sensitivity of SSEP to acute ischemia of the cord in such cases. At present, the only sure intraoperative test for anterior cord function is clinical assessment of voluntary motor activity, the "wake-up" test described by Vauzelle *et al.*[119]

The reliability of intraoperative SSEP monitoring thus seems reasonably satisfactory, but by no means absolute. Technical problems have been reported by several investigators, and reliability varies from one series to another. Enhanced reliability can be expected as technical difficulties are resolved and teams gain experience. No readily applicable intraoperative electrophysiologic monitor of anterior cord function has yet been described.

Brainstem auditory-evoked potientials. In 54 cases of BAEP monitoring during neurosurgical operations in

the cerebellopontine angle,[20] we found BAEP at the end of anesthesia to be reliable predictors of postoperative auditory and brainstem function. We saw no brainstem injuries, and the only instances of hearing loss were in five patients who required deliberate section of the eighth nerve. These five were the only patients who suffered irreversible intraoperative loss of BAEP. Even virtual obliteration of the BAEP, when reversible, was compatible with preservation of auditory function.[96,100]

In Raudzens' 66 cases of intraoperative BAEP monitoring,[83] ten patients developed delays in "BAEP latencies" (peak or peaks not specified) greater than 1.5 ms. All ten had postoperative decreases in hearing that cleared within 30 days. Six patients had irreversible loss of BAEP during operation; this happened in five patients despite a grossly intact auditory nerve. All six of these patients experienced profound hearing loss. Two of Raudzens' patients suffered brain damage intraoperatively. One had injury to the brain stem associated with uncontrollable cerebellar edema, and the BAEP past peak II was irreversibly lost. In the other patient, extensive cortical damage occurred during resection of a meningioma from the lateral ventricle, while BAEP were normal throughout the operation. Both of these cases are consistent with current knowledge about neural generators of specific peaks in the BAEP waveforms. Peak I, arising from the extracranial portion of the auditory nerve, and peak II, generated in the intracranial portion of the auditory nerve and/or the cochlear nucleus, could well be preserved in the face of injury to the upper brain stem. Since the entire BAEP is subcortical in origin, it could not be expected to reflect injury of the cerebral cortex.

Allen *et al.*[84] reported preservation of hearing and brain stem function in five patients whose BAEP were altered only transiently during operation. Three of Allen's ten patients had persistent BAEP deterioration. Two of these experienced loss of hearing as expected, but hearing was improved after operation in the third. We have seen recovery of BAEP at the end of operation after as long as 177 minutes of obliteration, with preservation of auditory function.[100] Presumably, the BAEP in Allen's patient recovered at some time after monitoring was stopped, but we do not know either the duration of recording or the time course of this patient's recovery.

Hashimoto *et al.*[122] monitored BAEP during 12 neurosurgical operations. Seven patients with stable waveforms and two with transient intraoperative changes in BAEP made uneventful recoveries, while two with BAEP deterioration that failed to resolve were damaged neurologically. Hashimoto's twelfth patient had stable waveforms during resection of a choroid plexus papilloma from the fourth ventricle, but lost the BAEP before awakening from anesthesia. This patient died three days later. This report suggests that, in at least some patients, electrophysiologic monitoring should be continued until patients have recovered sufficiently from anesthesia to allow clinical neurologic assessment.

The group at Children's Hospital of Pittsburgh saw stable, improved, or only transiently altered BAEP during eight of the ten neurosurgical operations they monitored (Bursick DM, McKeever R, Vries JK, Sclabassi RJ: unpublished). Neurologic function improved after four of these operations and was stable after one, but three patients had new neurologic deficits postoperatively (vertigo, loss of twelfth nerve function, and mild ataxia which slowly disappeared). Two patients in whom BAEP were lost due to technical difficulties or without obvious cause had major neurologic injuries. Bursick and his colleagues thought that damage in these cases occurred after monitoring was lost.

In summary, the reliability with which intraoperative BAEP predict postoperative neurologic function varies from one report to another. Reliability is greater in the larger series, suggesting that experience with recording and interpreting BAEP in the operating room environment can enhance the reliability of this monitoring technique.

Visual-evoked potentials. VEP have so far proved less reliable for intraoperative monitoring than either SSEP or BAEP. Despite an initial enthusiasm,[83,84] the two investigators with the most extensive experience are now somewhat disillusioned with the method (Raudzens P: personal communication; Starr A: personal communication).

During 62 successfully monitored operations on the pituitary gland or intracranial aneurysms, Raudzens[83] found 81% variability in the latency of the dominant positive peak of the VEP. He saw VEP alterations with induced hypotension and retraction of the optic chiasm that resolved with restoration of arterial blood pressure and release of retraction, but he also described both "false-positive" and "false-negative" results. Fifty-eight of Raudzen's patients had transient intraoperative changes in VEP and four had irreversible alterations. Two of the patients with irreversible deterioration of VEP had visual loss postoperatively. The other two developed intractable intracranial hypertension and died without recovering from anesthesia.

In the 22 of Allen's 25 patients with "technically satisfactory" VEP to diffuse flash stimulation, 15 had transient intraoperative alterations in VEP.[84] None of these 15 had changes in visual function postoperatively. Of the seven patients with persisting improvement of VEP after decompression of optic pathways, two had improved vision after operation.

The reliability of VEP for intraoperative monitoring may improve when more satisfactory stimulators and better recording techniques are developed.

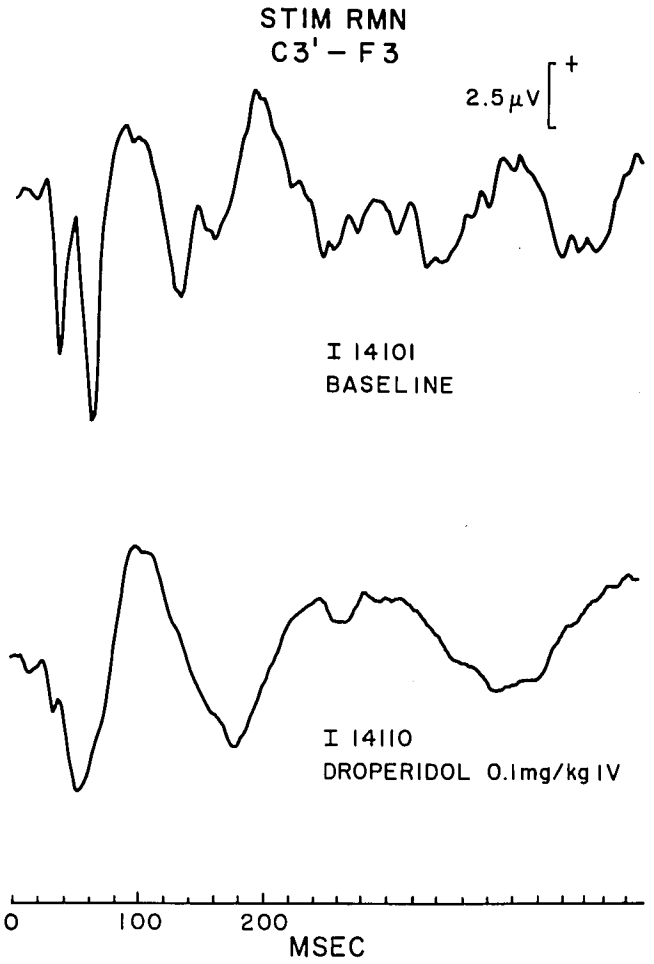

FIG. 9. Effects of premedication with droperidol on cortical somatosensory-evoked potentials. Note stability of the initial cortical positivity, approximately 25 ms after the stimulus. These waveforms were recorded using filters set at 0–90 Hz rather than the 1–1,500 Hz setting used for other figures in this paper, so that high frequencies are largely eliminated. Thus, artifact is less but some information may be sacrificed.

Problems and Controversies

Difficulties surrounding the use of SEP for monitoring neurologic function intraoperatively are to some extent typical of the problems that arise with the early diffusion of new technology. The complexity of the methodology may be a limiting factor in many settings, at least for a time.

EQUIPMENT

The systems used to record SEP are bulky, expensive, and not always easily portable. Many units require additional electrical isolation to meet safety requirements for the operating room, and special consideration must be given to avoidance of the sterile surgical field. Devices used to provide sensory stimulation in the diagnostic laboratory are not always appropriate during surgery. Refinement of equipment and techniques to minimize human error in the demanding environment of the operating room is still only rudimentary.

PERSONNEL

Considerable experience is required to record SEP accurately and interpret waveforms appropriately. Because equipment is somewhat complex, a relatively high level of operator training is needed. Some understanding must be gained with regard to use of both electroencephalographs and computers. Monitoring of SEP currently requires the full attention of a well-trained technician, as well as the ready availability of a neurophysiologist or physician experienced in interpreting SEP. When general purpose computers are used to record SEP, engineers and programmers are needed as well.

The physician responsible for recording and interpreting SEP may be a neurologist, neurosurgeon, or anesthesiologist. Because the neurologist may not be available to spend long hours in the operating room, and because the neurosurgeon may be hesitant to divert his attention from the operative procedure, interpretation of intraoperative changes in SEP may fall naturally to the anesthesiologist who becomes knowledgeable in this area.

Because interpretation of SEP waveforms rests largely on pattern recognition techniques, skill can be gained only through some combination of formal or informal training and practical experience. Furthermore, the team caring for the patient in the operating room must learn not only how to record and interpret SEP but also how to use the data provided by electrophysiologic monitoring of neurologic function. New methods of signal analysis,[123–127] once they are fully developed and automated, may ease the burdens of acquiring and interpreting SEP, but effective utilization of these techniques will continue to depend on active collaboration among neurosurgeons, neurophysiologists, and anesthesiologists.

CLINICAL PROTOCOLS

Methods of recording SEP in the operating room have not been standardized, and appropriate anesthetic techniques are not fully agreed upon. SEP, particularly those of cortical origin, can be altered by anesthetic agents[51,53,55] or even premedication[128–131] (see fig. 9). In some instances, an anesthetic otherwise appropriate for a particular patient might interfere with monitoring of SEP, so that either monitoring techniques or anesthetic techniques may require modification. Several potentially confounding variables must be monitored and

constrained, and a relatively constant pharmacologic and physiologic state must be maintained during critical monitoring periods. Finally, the appropriate responses to intraoperative alterations in SEP may not be readily apparent. Several therapeutic interventions associated with restoration of deteriorating SEP have been anecdotally described in the clinical literature, but indications for specific interventions are not always well-defined.

The lack of generally accepted clinical protocols increases the difficulty of establishing new programs and hampers comparisons of results obtained in different institutions, impairing the objective assessment of this new technology.

Reliability

The reliability with which intraoperative SEP findings predict postoperative neurologic function varies to some extent among the reported series, and several inaccurate predictions have been described. Technical difficulties, lack of experience, and lapses in quality control may explain some erroneous results. The extent to which a degree of unreliability may be inherent in the methodology cannot yet be determined.

The clinical data base relating intraoperative SEP to neurologic outcome is still relatively small, and quantitative characterization of SEP waveforms[132–135] is not yet fully developed. Tolerance limits for the acceptable degree and duration of intraoperative SEP alteration have not been defined. Absolute tolerance limits for intraoperative variation in SEP, however, are no more to be expected than are absolute tolerance limits for changes in temperature, heart rate, and arterial blood pressure.

Cost-effectiveness

In the face of pressures to restrain the increasing costs of health care, new programs require justification. Decisions about allocation of scarce resources are difficult, and few guidelines are available. One court has suggested that omission of monitoring may be negligent whenever the incidence of untoward events that could be prevented by monitoring times the anticipated cost of a single such event is greater than the cost of monitoring.[136] Use of this guideline is complicated by difficulties in estimating 1) the incidence of neurologic complications, 2) the costs of these complications, and 3) the reliability with which monitoring can prevent complications. If we estimate from the data of MacEwen *et al.*[137] that paraplegia occurs in 0.3% of patients undergoing spine fusion for scoliosis, and if we assume that paraplegia costs $200,000 per case, spinal cord function should be monitored during this operation if reliable monitoring can be provided for less than $600. Greater risk or greater cost of injury would, according to this guideline, justify greater expenditure. Conversely, diminished reliability of monitoring or a decreased possibility of preserving function through the use of monitoring presumably would decrease the allowable cost of monitoring.

Conclusions

Intraoperative monitoring of SEP offers promise as a means of reducing the incidence of neurologic injury during selected neurosurgical, orthopedic, and vascular operations. The techniques currently available may be useful whenever a sensory pathway amenable to monitoring is at risk or must be identified intraoperatively, but most experience has been with monitoring of SSEP during operations on the spine or spinal cord and monitoring of BAEP during operations in the posterior cranial fossa.

These electrophysiologic methods of monitoring neurologic function during anesthesia and surgery cannot be lightly undertaken, however. Controversies and limitations still surround this new technology. Equipment is bulky and expensive, techniques complex, quality control demanding, and interpretation difficult. The feasibility, sensitivity, utility, and reliability of these techniques may well improve as additional information is gained from experiments in animals and careful observations in patients. Within the next several years, intraoperative monitoring of SEP can be expected on a routine basis for selected operations, not only in most large medical centers but also in many community hospitals.

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