

Intraoperative Somatosensory Evoked Potential Monitoring Predicts Peripheral Nerve Injury during Cardiac Surgery

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Background: Brachial plexus injury may occur without obvious cause in patients undergoing cardiac surgery. To determine whether such peripheral nerve injury can be predicted intraoperatively, we monitored somatosensory evoked potentials (SEPs) from bilateral median and ulnar nerves in 30 patients undergoing coronary artery bypass surgery.

Methods: SEPs were analyzed for changes during central venous cannulation and during use of the Favoloro and Canadian self-retaining sternal retractors, events hereto implicated in brachial plexus injury. Brachial plexus injury was evaluated during physical examination in the postoperative period by an individual blinded to results of SEP monitoring.

Results: Central venous cannulation was associated with transient changes in SEPs in four patients (13%). These changes occurred intermittently during insertion of the cannula but completely resolved within 5 min. Postoperative neurologic deficits did not occur in these cases. Use of the Canadian and Favoloro retractors was associated with significant changes in 21 patients (70%). In 16 of these, waveforms reverted toward baseline levels intraoperatively and were not associated with postoperative neurologic deficits. Five patients demonstrated a neurologic deficit postoperatively. In each of these, SEP change associated with use of surgical retractors persisted to the end of surgery compared to the immediate pre-bypass period.

Conclusions: Intraoperative upper extremity SEPs may be used to predict peripheral nerve injury occurring during cardiac surgery. (Key words: Complications: brachial plexus injury; surgery, cardiac. Monitoring: somatosensory evoked potentials.)

BRACHIAL plexus injury remains a common and serious complication following open heart surgery. In previously reported prospective studies,¹⁻⁷ the incidence of upper extremity nerve injury ranged between 2% and 18%. Factors implicated include traumatic injury during central venous cannulation and stretch or compression injury associated with the use of surgical retractors.^{1,4,6,7} Intraoperative somatosensory evoked potential (SEP) monitoring has previously been shown to minimize the risk of sciatic nerve injury during hip surgery.^{8,9} In this study we used SEPs in a similar fashion in an attempt to minimize risk to the brachial plexus during cardiac surgery. We recorded the SEPs from right and left median and ulnar nerves both preoperatively and continuously during surgery to determine whether significant changes in SEPs accompanied the clinical events thought to be associated with brachial plexus injury. Patients were examined postoperatively to determine whether peripheral nerve injury had occurred. Finally, the relationship between SEP changes and neurologic injury was examined.

Materials and Methods

Following approval by the Hospital Investigational Review Board, informed consent was obtained from 30 consecutive patients undergoing elective coronary artery bypass surgery. Each patient was assessed by preoperative physical examination to be neurologically normal. Patients were positioned on the operating table with both arms by their sides. Foam pads were wrapped around each elbow to protect the ulnar nerve. The head was placed in the midline position and rested on a foam head ring.

The Favoloro retractor was used to facilitate dissection of the internal mammary artery in 29 patients (a vein graft alone was used in only one patient). This is a self-retaining sternal retractor consisting of two ver-

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tical bars upon which is suspended a horizontal rod. The vertical bars are attached to one side of the operating table adjacent to the arm. Traction is exerted by screwing on a retractor from the free edge of the divided sternum to the horizontal rod. Following removal of the Favoloro retractor the Canadian (*i.e.*, sternal) retractor was inserted in all 30 cases during the grafting procedure. This second type of self-retaining retractor consists of two metal blades applied to either side of the divided sternum. The crossbar is perpendicular to the blades and can be adjusted to regulate the extent of chest retraction. Surgery was performed *via* a median sternotomy, and the width of chest retraction was measured in centimeters in each case.

Anesthesia

Patients were premedicated with 0.1 $\mu\text{g}/\text{kg}$ morphine sulfate intramuscularly, 0.4 mg scopolamine intramuscularly, and 0.1 mg/kg diazepam orally prior to surgery. Anesthesia was induced using 10 $\mu\text{g}/\text{kg}$ sufentanil iv and 3 mg midazolam iv and was maintained with an infusion of 2.5 $\mu\text{g}/\text{kg}/\text{h}$ sufentanil and 1 mg/h midazolam. Oxygen was the only inspired gas used during the study. Neuromuscular blockade was provided with vecuronium and pancuronium. Intraoperative hypotension, hypertension (defined as a 15% change from baseline), and myocardial ischemia (defined as 0.1 mV ST segment displacement) were treated with intravenous phenylephrine, trimethaphan, and nitroglycerin, respectively. During the measurement period, hemodynamic stability was maintained within the predefined limits.

SEP Recordings

Cortical SEPs from right and left ulnar and median nerves were recorded using the Cadwell Spectrum 32 Sentry program (Cadwell Laboratories, Kennewick, WA). Silver-silver chloride self-gelled electrical stimulating electrodes were placed over the median nerve at the wrist and over the ulnar nerve at the elbow initially, but following the occurrence of an isolated distal ulnar nerve motor deficit, the ulnar nerve was thereafter stimulated at the wrist in 15 cases. Stimulus parameters included constant current stimulation at a stimulus rate that randomly varied between 3.91 and 4.97 Hz, 100- μs pulses, and a stimulus strength set at 1.5 times motor threshold.

Cup recording electrodes were attached to the scalp with collodion and placed at the C4', C3', and Fz lo-

cations as defined by the international 10–20 system.¹⁰ All impedances were less than 2 k $\cdot\Omega$. To detect changes in latency and amplitude of continuously acquired SEPs, the Sentry program requires an initial collection of SEP baselines. Each baseline consisted of a grand average of 10 subaverages, each subaverage representing the evoked response induced by 100 stimulus repetitions. All SEPs were digitally filtered using optimal digital filtering determined by the phase synchrony method.^{10,11} A peak or trough in each SEP (usually the N19 peak or the P22 trough) was chosen as the feature for programmed automatic detection for the monitoring session. A mean and standard deviation (SD) was calculated for each feature.

Baseline SEPs were collected at two intervals: (1) after premedication but prior to central venous cannulation and (2) after induction of anesthesia. The Sentry program cycled sequentially between right and left ulnar and median nerves on four recording channels. Post-cannulation SEPs were compared to the precannulation baseline and intraoperative SEPs were compared to the post-induction baseline for latency and amplitude changes. Somatosensory evoked potentials changes were considered significant when latency and/or amplitude exceeded 3 SD. Particular attention was paid to SEP changes occurring during central venous catheter insertion and during Favoloro and Canadian retractor placements. At the conclusion of surgery SEPs were grouped into one of three categories: (1) normal = SEP latencies and amplitudes were within 3 SD of baseline values; (2) improved = SEPs that showed a ≥ 3 SD change prior to cardiopulmonary bypass but whose amplitude and latency were less than the maximum prebypass change at the conclusion of surgery; and (3) absent = persistently flat SEP traces or waveforms that showed a ≥ 3 SD SEP change that did not improve by the conclusion of surgery. All SEP baselines and updated responses were stored on magnetic disks.

Neurologic Examination

Patients were examined within 24 h of completion of surgery. All patients were awake, alert, and cooperative during assessment. The upper limb dermatomes were assessed for decreased touch, pain, vibratory, and proprioceptive sensations. The major muscle groups of the upper limb were tested for power and graded 0–5.¹² Neurologic examinations were performed by a

SEPs PREDICT PERIPHERAL NERVE INJURY DURING SURGERY

member of the research team who was unaware of the results of the SEP monitoring.

Statistical Methods

Fisher's exact test was applied to all categorical data. A *P* value of less than .05 was considered significant. A nonparametric ANOVA using the Kruskal-Wallis test followed by the Wilcoxon's rank sum test was used to establish significance between the width of chest retraction and the occurrence of significant SEP changes or neurologic deficit.

Results

Somatosensory evoked potentials were satisfactorily recorded and analyzed for each of the 30 patients. A 3 SD change in latency corresponded to an average increase of $7.5\% \pm 7.2\%$ (SEM) and $9.0\% \pm 5.2\%$ for the median and ulnar nerves, respectively. A 3 SD percent change in amplitude corresponded to an average change of $59.8\% \pm 37.3\%$ and $62\% \pm 29.2\%$ for the median and ulnar nerves, respectively. These values representing the percentage change of latency and amplitude in terms of 3 SD were obtained using both the awake and post-induction baseline.

Hemodynamic variables were recorded and maintained within normal limits in all 30 patients. Seven of the 30 patients (23%) had normal SEPs recorded for the entire monitoring session. Twenty-three patients (77%) were noted to have significant SEP changes during at least one of the three events of interest (*i.e.*, central venous cannulation, Favoloro and Canadian retractor placement). Of these, 18 patients had SEPs that became normal or showed less than 3 SD change at the conclusion of surgery compared to that noted in the pre-bypass period. At the completion of surgery, five of the patients (22%) had either persistently flat waveforms or showed greater than 3 SD change in SEPs compared to pre-bypass status. Figures 1 and 2 illustrate examples of these respective types of changes.

Table 1 lists by patient: (1) the condition of the SEPs at the end of surgery, (2) the type of peripheral nerve deficit found 24 h after surgery, and (3) the perioperative event occurring just prior to a significant SEP change.

Six patients (20%) were found to have peripheral nerve deficits 24 h postoperatively. The neurologic deficits included four sensory, one motor, and one combined sensory and motor deficit. In all but two of these

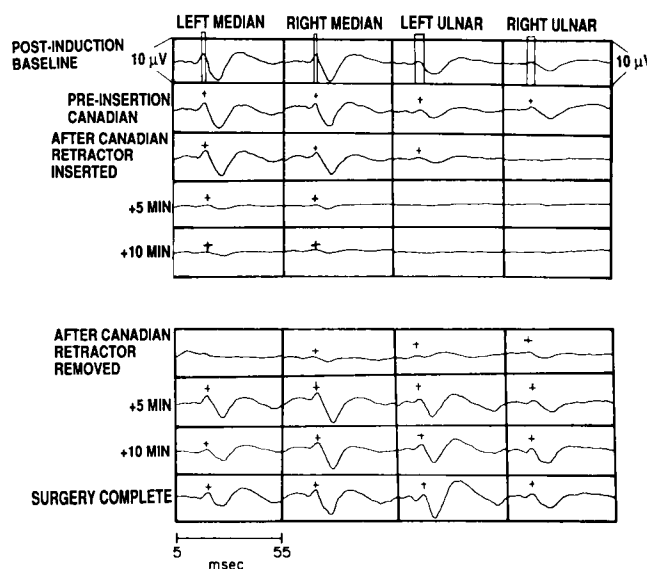


Fig. 1. Changes in cortical somatosensory evoked potentials (SEPs) elicited by electrical stimulation of ulnar and median nerves during insertion and removal of the Canadian retractor (patient 6). At the top of each column of waveforms is the post-induction SEP baseline response used for on-line automated comparisons. The SEP feature followed in selected updates below is bounded by two vertical lines representing the 99% confidence limits for latency change. The operative events corresponding to the displayed SEPs are labelled to the left of each row of SEP updates. The presence of a plus sign over a SEP indicates the detection of the waveform component of interest. Note the attenuation of bilateral SEPs following insertion of the Canadian retractor. Improvement toward normal in all SEPs at the completion of surgery correctly predicted the absence of neurologic deficits postoperatively. The amplitude calibration (μV) for all waveforms is shown to the left of each baseline SEP. Negative waveform excursions are up for all of the SEPs. Time calibration for all traces (ms) is located at bottom left of the figure.

six patients, evidence of peripheral neurologic injury had resolved at the time of discharge from hospital.

Right internal jugular venous cannulation was associated with significant SEP changes in four patients (13%). These changes were of short duration (5 min) and disappeared in all cases prior to the induction of anesthesia. Placement of the Favoloro retractor produced significant SEP changes in 17 of 29 patients (58%). Of these, 14 patients demonstrated recovery toward baseline levels following placement or eventual removal of this retractor, while in 3 patients (10%) the changes persisted during use of the Canadian retractor. Seventeen patients (56%) had significant changes during chest retraction with the Canadian retractor. Twelve of these patients already had shown significant changes during use of the Favoloro. Of these

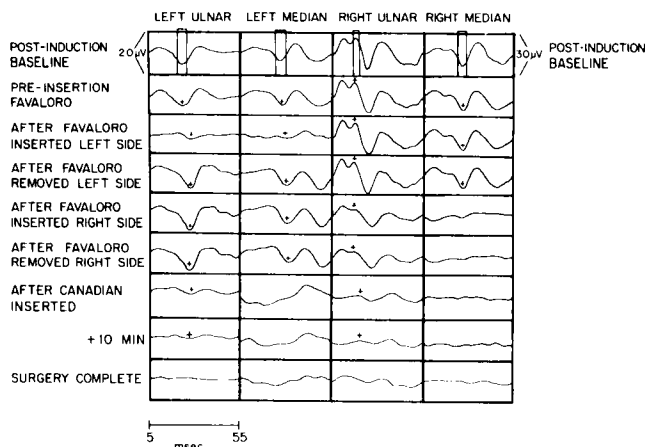


Fig. 2. Changes in cortical SEPs elicited by electrical stimulation of the median and ulnar nerves during insertion and removal of the Favoloro and Canadian retractors (patient 7). The SEP changes are depicted using the same format as in figure 1. Note that the amplitude scale for SEPs recorded on the left side ($2 \mu\text{V}/\text{division}$) differs from those obtained by stimulation of the right median and ulnar nerves ($3 \mu\text{V}/\text{division}$). Somatosensory evoked potentials were lost on the left side during left Favoloro placement. With removal of the Favoloro retractor, the SEPs recovered. Likewise, SEPs on the right side became attenuated with right Favoloro placement. With Canadian retractor placement, all SEPs became attenuated and remained flat at the end of the operation.

12 cases, 3 continued to demonstrate the changes produced by the Favoloro retractor (each of these 3 patients developed a postoperative neurologic deficit), and 9 showed a progression of the SEP change and/or a significant change (≤ 3 SD) in one or more additional nerves (one of these patients developed a postoperative neurologic deficit). In the remaining patient the SEP latency and amplitude change slowly returned to normal while the Canadian retractor was still in place. Thus, significant SEP waveform changes occurred *de novo* in five patients (17%) following deployment of the Canadian retractor (one of these patients had a postoperative neurologic deficit). Therefore, neurologic injury appeared to be associated with the Favoloro retractor in three cases and with the Canadian retractor in two cases.

At the conclusion of surgery analysis of the SEP waveforms retrieved for five of the six patients manifesting peripheral nerve deficits postoperatively demonstrated continued or increasing deterioration in the SEP change compared to the pre-bypass SEP response. A review of the particular type of SEP change in the immediate pre-bypass period in each of these cases showed that significant changes were present in both latency and am-

plitude. Patients who showed a significant change in either latency or amplitude alone at this time did not develop neurologic injury. In the remaining 25 cases, SEP waveforms that were abnormal had either returned to normal or demonstrated a change in amplitude and/or latency less than that seen in the pre-bypass response. One of these 25 patients (patient 11) developed an isolated motor deficit of the distal ulnar nerve. Both intraoperative and postoperative SEP studies were normal in this patient. Postoperative motor evoked potentials confirmed the clinical finding. Further reference is made to this patient in the discussion.

Sternal separation by the Canadian retractor ranged between 11 and 16 cm, (12.4 ± 0.9 cm: mean \pm SD) in those patients who did not develop a postoperative

Table 1. Sensory Evoked Potential (SEP) Changes and Postoperative Neurologic Deficit

Patient No.	CVP	Favoloro	Canadian	SEP at End of Surgery	Neurologic Deficit
1	-	-	-	Normal	-
2	-	+	-	Normal	-
3	+	-	-	Normal	-
4	-	+	+	Improved	-
5	+	+	+	Improved	-
6	-	-	+	Improved	-
7	-	+	+	Absent	S
8	-	+	+	Absent	S
9	-	+	+	Improved	-
10	+	+	+	Absent	S
11	-	-	-	Normal	M
12	-	+	+	Improved	-
13	-	-	+	Improved	-
14	-	+	+	Absent	S, M
15	-	+	+	Improved	-
16	-	-	-	Normal	-
17	-	O	-	Normal	-
18	-	+	-	Normal	-
19	-	+	+	Improved	-
20	-	-	-	Normal	-
21	-	+	+	Improved	-
22	-	+	-	Improved	-
23	-	-	-	Normal	-
24	-	+	+	Improved	-
25	-	-	-	Normal	-
26	-	+	-	Improved	-
27	-	-	+	Absent	S
28	-	-	+	Improved	-
29	-	+	-	Improved	-
30	+	-	+	Improved	-

\pm - presence or absence of significant SEP changes associated with the event; S - sensory deficit postoperatively; M - motor deficit postoperatively; O = Favoloro retractor not used.

SEPs PREDICT PERIPHERAL NERVE INJURY DURING SURGERY

neurologic deficit. In the six patients who demonstrated postoperative neurologic injury, the magnitude of sternal separation ranged between 11.5 and 14 cm (12.6 ± 0.9 cm). The magnitude of sternal separation was shown to be unrelated to the development of postoperative peripheral nerve deficits ($P = .35$) or the presence of significant SEP changes ($P = .71$).

Discussion

These data confirm reports that brachial plexus injury is common following cardiac surgery.^{4,6} Twenty percent of patients had evidence of a nerve deficits 24 h after surgery, however only 6% retained their deficits 1 week postoperatively, a complication rate that agrees with that of other studies.

Two important observations arise from this study. First, major changes in waveform morphology resulting in flat waveforms or the persistence or progression of significant SEP changes noted in the immediate pre-bypass period to the conclusion of surgery are reliable indicators of clinical neurologic injury. On the other hand, SEPs at the conclusion of surgery that showed less than 3 SD change compared to the pre-bypass change were not related to the development of postoperative neurologic injury. Second, changes greater than 3 SD are associated with sternal retraction and not with central venous cannulation. The electrophysiologic monitoring techniques described demonstrated 100% sensitivity (for sensory nerve dysfunction) and 100% specificity in predicting peripheral sensory nervous system injury.

The use of our response criteria requires comment. A 3 SD change was chosen based on work carried out by York *et al.*¹³ In a series of 81 patients undergoing correction of spinal deformities or spine fractures in whom SEP monitoring was performed, changes in latency of up to 15% and amplitude of 50% corresponded to a 2 SD change without compromising spinal cord function. The large standard deviations associated with these latency and amplitude changes reflect the normal variability of SEPs. The statistical approach used to define the degree of significant SEP change is a more accurate estimation than using an arbitrary (*e.g.*, 50% decrease in amplitude) percentage change, because it takes into account the inherent variability of each patient's intraoperative SEPs. Because of the absence of intraoperative wake-up tests and the fact that reliable sensory examinations can only be made when patients have recovered from anesthesia, we suggest that the

status of the SEPs at the conclusion of surgery can be used to predict postoperative peripheral nerve deficits.

The results of this study indicate that variable degrees of neurologic deficit occur, both in terms of severity and duration. Normal or improving SEP waveforms at the end of the operation indicate minor peripheral nerve dysfunction that improves within the operative period. The continued presence or progression of a significant change toward a flat line trace reflects severe dysfunction that will be detected clinically postoperatively. Presumably, the degree of dysfunction is related to the degree of stretch or ischemic injury that occurs during the operation. This would explain the observation that, while 20% of patients demonstrated a peripheral nerve deficit 24 h postoperatively, the extent of injury and/or the ability of the nerve to recover was such that only 6% of patients retained their deficits 1 week later. Observation of the waveforms prior to beginning bypass also showed that in those five patients who had a postoperative nerve deficit, the significant changes were persistent and showed both latency and amplitude changes greater than 3 SD. Although significant changes occurred in 17 other patients, these were either transient or occurred in only latency or amplitude. These changes most likely represent transient nerve injury that recovers quickly. Thus, it is possible to predict patients at risk for developing a neurologic deficit prior to going on bypass. Appropriate intervention at this stage may prove beneficial.

The etiology of injury remains unclear. In our study, central venous cannulation was not associated with postoperative neurologic deficit. Unlike the results of Hanson *et al.*,⁶ our results support the work of Tomlinson *et al.*¹⁴ and Roy *et al.*,¹ which indicate that central venous cannulation through the internal jugular vein does not appear to cause peripheral nervous system injury. One reason for this result may be related to the fact that internal jugular cannulation was carried out in awake but sedated patients. These patients were able to alert the anesthesiologists when the cannulation needle approached or touched the brachial plexus. We acknowledge, however, that the number of patients in this study is too small to conclude a definite negative effect. Neurologic impairment appeared to be associated with the use of sternal retractors, however, it was not possible to definitely ascribe injury to any particular retractor. Twenty-one patients (70%) showed a significant SEP change at some stage during the use of either the Favoloro SEP change at some stage during the use of either the Favoloro or Canadian retractor. In

16 of these, the SEP change was transient and associated with the actual positioning of the retractor. In these cases the SEPs returned to normal quickly once the retractor was in place (5–10 min). Previous authors working with cadavers have suggested that injury is due to penetration of the brachial plexus by fractured first ribs.³ Although the overall incidence of significant SEP changes is high during the use of both types of retractors, the majority of these changes are transient. Therefore it seems reasonable to suggest that the fault is attributed to a temporary phenomenon such as stretching or ischemia of the brachial plexus. Protrusion of fractured ribs into the brachial plexus may account for more serious injuries but is unlikely to explain the transient SEP changes noted in most patients. Stretching or ischemia may occur while placing the retractor in the correct position, recovery occurring once it is placed. Postoperative neurologic deficits may result from more extensive stretch or ischemia from which the brachial plexus has not recovered fully at the time of the postoperative neurologic examination. Somatosensory evoked potential waveforms that show improvement compared with the initial magnitude of SEP changes seen shortly after retractor placement represent those patients in whom recovery is actually taking place and has been completed at the time of neurologic assessment. Previous studies also have suggested that neurologic injury may be associated with the width of chest retraction.^{4,6} While this fact was not substantiated in this study, the range of widths examined was small and further study is required.

Certain further limitations exist in this study. First, damage to the ulnar nerve below the level of the elbow was not studied in 15 patients. The ulnar nerve was initially stimulated at the elbow to ensure isolation. However, following the occurrence of a motor deficit in the forearm in one patient, the remaining 15 patients were assessed using stimulation of the ulnar nerve at the wrist. Second, the Sentry program cycles between four channels and therefore allows monitoring of only four nerves sequentially. Consequently, it was not possible to study the radial nerve. While reports of damage to the radial nerve exist,¹⁵ the median and ulnar nerves have been implicated most frequently in injury⁶ and were therefore chosen for investigation.

The false negative result obtained in patient 11, who developed a motor nerve deficit postoperatively, was not predicted by SEP monitoring. However, as postoperative neurologic sensory examination was normal,

this is not an unexpected finding. In addition, the site of stimulation was at the elbow and therefore proximal to the site of injury. With regard to this latter point, however, normal SEPs were collected postoperatively using distal ulnar stimulation (*i.e.*, the wrist) at the time of the patient's abnormal neurologic examination. In any event, this case highlights the limitation of SEP monitoring, as only sensory deficits can be predicted reliably. Other SEP monitoring applications (*e.g.*, spinal cord procedures) suffer similar limitations.¹¹

In conclusion, SEP monitoring has been shown to be capable of predicting peripheral nervous system injury. Further study is required to examine whether neurologic outcome is improved by adjusting surgical technique when significant SEP changes are seen. With the advent of technically simpler and less time-consuming methods, intraoperative SEP monitoring may be of benefit in all types of surgery when there is an inherent risk of neurologic damage. In addition, SEP monitoring has potential use in the development of operative techniques and instruments designed to minimize iatrogenic peripheral nerve injury.

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SEPs PREDICT PERIPHERAL NERVE INJURY DURING SURGERY

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