An Evaluation of the Information Gained from the Use of Intraoperative Nerve Recording in the Management of Suspected Brachial Plexus Root Avulsion

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Background: The authors examine the information gained from the use of intraoperative nerve recording in the management of suspected brachial plexus root avulsion.

Methods: A retrospective chart review examined 25 patients who had undergone intraoperative nerve recording for a brachial plexus injury. Thirty-seven preganglionic root avulsions were demonstrated by somatosensory evoked potentials, C4 to T1, during intraoperative nerve recording. To measure the information gain derived from intraoperative nerve recording, the authors compared the number of roots diagnosed as preganglionic root avulsions preoperatively to those diagnosed by intraoperative nerve recording. From this, the authors can demonstrate the positive and negative predictive values of their preoperative multimodality assessment for brachial plexus root avulsion and compare this to the result of intraoperative nerve recording to derive the gain of information. In addition, the authors examined the validity of the intraoperative nerve recording somatosensory evoked potentials when this produced a diagnosis of an intact root in this cohort by performing a clinical outcome analysis for those roots used for reconstruction.

Results: Twenty-five patients underwent intraoperative nerve recording for unilateral brachial plexus injury; 15 patients were diagnosed with 55 preganglionic root avulsions from C4 to T1 preoperatively by multimodality assessment. Fourteen of 55 roots thought to be avulsed preoperatively were found to be intact with intraoperative nerve recording, representing a gain of information of 25 percent derived from intraoperative nerve recording for roots thought to be avulsed preoperatively.

Conclusion: Intraoperative nerve recording adds useful information during exploratory brachial plexus surgery. (*Plast. Reconstr. Surg.* 127: 1237, 2011.)

The more accurately a surgeon can assess the nature of a root avulsion, the better the results of brachial plexus reconstruction.[1] The brachial plexus may be damaged at a preganglionic or postganglionic level. Permanent postganglionic injuries are amenable to direct surgical manipulation by repair, grafting, or neurolysis. Conversely, when the plexus roots undergo preganglionic avulsions, nerve transfers, neurotization, and free muscle transfers must be deployed in combination with other reconstructive procedures.[1]

Brachial plexus injuries are frequently closed avulsions, and these injury patterns are usually complex, combining both preganglionic and postganglionic components.[2] A surgical plan must attempt to make use of those nerve roots and plexus donors that are intact, to compensate for those that are avulsed. Furthermore, an intact root on surgical inspection with no clinical function pre-

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operatively poses a dilemma for the surgeon because of a lack of information.[1,2] Either it has been avulsed at a preganglionic level and should not be used or it is intact and the opportunity to make early use of it in the reconstructive strategy must not be missed. Imaging studies such as computed tomographic myelography and magnetic resonance imaging are also helpful.[3,4] However, anatomical continuity demonstrated by imaging studies or direct perioperative surgical observation does not necessarily guarantee the presence of functional continuity by intraoperative nerve recording.[5]

It is with this problem that intraoperative nerve recordings are reported to be useful in the management of brachial plexus injuries.[6–10] The aim of this study was to examine the information gained by intraoperative nerve recording in the operative management of brachial plexus injuries. The following null hypothesis was fashioned: intraoperative nerve recording adds no additional value to the preoperative diagnosis of root avulsion in the management of brachial plexus injuries.

PATIENTS AND METHODS

A retrospective chart review was conducted on a consecutive series of patients who had undergone intraoperative nerve recordings for brachial plexus injuries over a 12-year period. Twenty-six patients with unilateral brachial plexus injuries were identified; one patient was excluded because of the lack of a clearly defined preoperative diagnosis. The mean age of the patients was 32 years (range, 15 to 55 years). The data gathered included the preoperative diagnosis and intraoperative nerve recording results coupled with the reconstructions performed and clinical outcome data. The main objective data were the preoperative assessment of preganglionic root integrity and the intraoperative nerve recording results. The principal outcome data were the correlation between our preoperative data and the intraoperative nerve recording data in addition to the Medical Research Council muscle power grade of the reinnervated muscle for that root. In this study, it is possible for an intact root to have downstream injuries; we are examining the preganglionic root integrity.

The patients were followed up for an average of 22 months from their last procedure. For the 40 roots shown by intraoperative nerve recording to be in continuity with the brain, between one and three subsequent procedures were performed to achieve maximum functional outcome.

For the purposes of this retrospective chart review, we have examined two groups. The first group consists of those patients who had a preoperative diagnosis of preganglionic root avulsions, which is matched with the perioperative intraoperative nerve recording result for those roots. The second group consists of those patients with a negative preoperative diagnosis for preganglionic root avulsions, which is then matched to the intraoperative nerve recording results for those roots. This enables the study to provide the positive and negative predictive values of multimodality preoperative assessment in comparison with intraoperative nerve recording, from which we can infer the additional value of performing intraoperative nerve recording. Statistical analysis was achieved by two-way contingency tables (Tables 3 through 5) with a 95 percent confidence interval.

Intraoperative Nerve Recording Method

Our intraoperative nerve recording technique includes the use of somatosensory evoked potentials, nerve conduction studies, nerve root potential recordings, evoked motor action potentials, and nerve action potentials. Our technique has already been published in detail and is not described here.[1] This study focuses on the intraoperative somatosensory evoked potentials result, a component of the intraoperative nerve recording.

RESULTS

Preoperative versus Intraoperative Nerve Recording Evaluation Results

The results for 77 roots in 25 patients examined by intraoperative nerve recording for the assessment of brachial plexus injury were available (Table 1). For these cases, the preoperative diagnoses varied from one to six cervical root avulsions (C4 to T1). The preoperative summary diagnoses were achieved with variable contributions from the clinical examination, medical imaging (i.e., myelography, computed tomography, or magnetic resonance imaging), and electrodiagnostic testing (i.e., electromyelography, nerve conduction studies, or somatosensory evoked potentials). Based on this summary diagnosis, 55 of 150 roots (37 percent) were diagnosed as avulsed preoperatively. Conversely, 95 of 150 roots were thought to be intact at this time. Intraoperative nerve recording was not used to examine every root. Of the 77 roots that were examined by intraoperative nerve recording, 37 were found to have preganglionic root avulsions and 40 were determined to

Table 1. Preoperative versus Intraoperative Nerve Recording Evaluation Results

	Roots	Cases
Preoperative multimodality root assessment		
Total no. of roots examined	150.0	25.0
Preop = PGRA	55.0	15.0
Preop = intact root	95.0	24.0
IONR results		
Total no. of roots assessed by IONR	77.0	25.0
IONR = PGRA	37.0	15.0
IONR = intact root	40.0	17.0
Correlation between multimodality preoperative root assessment and IONR (correlation coefficient = 0.79)		
Total no. of roots assessed both Preop and by IONR	77.0	25.0
IONR = intact root: Preop = intact root	26.0	10.0
IONR =PGRA: Preop = PGRA	35.0	14.0
IONR = Intact root: Preop = PGRA	14.0	7.0
IONR = PGA: Preop = intact root	2.0	1.0
IONR changed Preop root diagnosis	16.0	8.0
IONR did not change Preop root diagnosis	61.0	17.0

IONR, intraoperative nerve recording root assessment; PGRA, preganglionic root avulsion; Preop, preoperative multimodality root assessment.

be in continuity with the central nervous system. The true incidence of preganglionic root avulsions diagnosed by intraoperative nerve recording in our population undergoing intraoperative nerve recording was therefore 27 percent of the 150 potential roots.

To assess the gain of information, we have correlated the intraoperative nerve recording result with the preoperative multimodality examination. We shall examine those results for which we have both sets of data. Intraoperative nerve recording modified the preoperative diagnosis for root avulsions in eight of 25 patients (32 percent), involving 16 of 77 roots (21 percent) examined by intraoperative nerve recording. This included two roots that were found to be avulsed that had preoperatively been considered intact. Intraoperative nerve recording was most valuable at identifying functioning intact roots that had preoperatively been thought to be avulsed. Fourteen of 55 roots preoperatively thought to be avulsed were found intact when they were subsequently tested by intraoperative nerve recording (25 percent); this enabled these roots to be used immediately for cable grafting, neurolysis, or neurotization to reinnervate the damaged plexus. Therefore, for those roots already suspected of being avulsed, there is a gain in information for 25 percent of roots derived from intraoperative nerve recording (Table 1).

In addition, intraoperative nerve recording provided confirmation of the preoperative preganglionic root avulsion diagnosis in 35 of 77 roots examined by intraoperative nerve recording, endorsing salvage procedures to be performed during surgery such as nerve and tendon transfers. Conversely, only two roots were found to be avulsed by intraoperative nerve recording that had preoperatively been thought to be intact (Table 1).

Clinical Results of Roots Used in Brachial Plexus Reconstruction

Of the 14 roots diagnosed intact by intraoperative nerve recording that were preoperatively thought to be avulsed, 11 were used for reconstruction by grafting, neurotization, and neurolysis in seven patients. The functional outcome based on 100 percent of the cases was a power of between M3 and M5 in nine of 11 roots (82 percent) (Table 2). This compared with 14 of 20 grafted roots (70 percent) overall based on 20 of the 21 cases that had the results recorded.

DISCUSSION

We have shown that there was a change of diagnosis in 21 percent of the roots and 32 percent of the patients examined using intraoperative nerve recording. The most useful information gain was

Table 2. Clinical Outcomes Comparing Those Roots Discovered by Intraoperative Nerve Recording to Be Intact* Compared to the Whole Group of Intact Roots Used for Brachial Plexus Reconstruction

	No. of Roots	No. of Patients	Power per Nerve		Procedures with Recorded Results (%)	Procedures Achieving M3–M5 (%)
			M1–M2	M3–M5		
All intact roots used for grafting or transfer or neurolysis	21	10	6	14	95.2	70.0
IONR intact: preoperative PrGRA roots used for reconstruction (neurolysis, nerve transfer, and/or grafting)	11	7	2	9	100.0	81.8

M, Medical Research Council power grade; PrGRA, preganglionic root avulsion; IONR, intraoperative nerve recording root assessment.
*The subgroup of roots was considered avulsed by multimodality preoperative assessment but transpired to be intact when tested intraoperatively by somatosensory evoked potentials during our intraoperative nerve recording.

seen for those roots that we had thought were avulsed at a preganglionic level that transpired to be intact, producing a positive intraoperative nerve recording signal (25 percent). The null hypothesis that intraoperative nerve recording adds no value to the preoperative diagnosis of root avulsion in the management of brachial plexus injuries was rejected. To examine whether using these roots was clinically useful, we have looked at the outcomes for those roots that were used in brachial plexus reconstruction that had been considered preganglionic root avulsions preoperatively but which intraoperative nerve recording had found intact perioperatively. These procedures included grafting, neurotization, and neurolysis. We found that these results compared favorably to all roots grafted in this series (Table 2), confirming that the intraoperative nerve recording was correctly identifying clinically useful roots with outcomes similar to those we already thought were intact.

Clinicians diagnose root avulsion by preoperative clinical observations such as the absence of a Tinel sign and the presence of a Horner syndrome or hemidiaphragm paralysis. Likewise, electromyelographic evidence of denervation of the paravertebral muscles or normal sensory nerve conduction velocities in an anesthetic area denotes a preganglionic lesion.[11] Imaging studies such as computed tomographic myelography and magnetic resonance imaging are also helpful.[3,4] However, anatomical continuity demonstrated by imaging studies or even direct surgical observation does not necessarily guarantee the presence of functional continuity.[1,5]

Our study also tests the preoperative multimodality diagnosis for root avulsion when comparing it to intraoperative nerve recording, which for the purposes of analysis we have used as the criterion standard (Table 3). We would like to stress that although intraoperative nerve recording is not universally accepted as the criterion standard, we feel that it represents the best available option at this time. The chance that any preoperative diagnosis of preganglionic root avulsions is correct (positive predictive value) was calculated as 71 percent, with a 95 percent confidence interval of 64 to 74 percent. There is a 93 percent chance (95 percent confidence interval, 80 to 98 percent) that a preoperative diagnosis of any root being not avulsed (therefore intact) is correct (negative predictive values). The sensitivity of the preoperative diagnosis, being the percentage of true avulsions that were picked up by the preoperative diagnosis, was 95 percent. The preoperative specificity of this diagnosis, being an expression of the proportion of healthy roots correctly identified preoperatively, was 65 percent. The low specificity and positive predictive value of the preoperative workup is our main indication for intraoperative nerve recording, reflecting that we are overdiagnosing preganglionic root avulsions before exploratory surgery. These statistics represent clinically useful data when relying on preoperative multimodality assessment of brachial plexus injuries and emphasizes the importance that intraoperative nerve recording has to play.

Our intraoperative nerve recording technique includes the use of somatosensory evoked potentials, nerve conduction studies, nerve root potential recordings, evoked motor action potentials, and nerve action potentials. Nerve action potentials are recorded directly from the nerve using bipolar electrodes and are valuable for evaluating the functional status of mixed peripheral nerves and for localizing a lesion in the nerve branches distal to the dorsal root ganglion. Any neuromas that are identified during the surgical exploration can further be investigated with nerve conduction studies or by triggered electromyography.

Somatosensory evoked potentials may help to evaluate the functional continuity between a cord or nerve root and the brain and between the dorsal root sensory fibers and the spinal cord. As many as 11 percent of patients with brachial plexus avulsions, however, have been reported to have partial root avulsions such as intact ventral rootlets and avulsed dorsal rootlets or vice versa.[4] Intraoperative somatosensory evoked potential recordings can be used to evaluate the afferent sensory tracts, but no information can be obtained regarding the condition of the anterior rootlets. This limitation may lead to a false-positive or false-negative so-

Table 3. Two-Way Contingency Table Analysis for Our Preoperative Multimodality Assessment versus Somatosensory Evoked Potentials in Our Intraoperative Nerve Recording

Preoperative Diagnosis	SEP = PrGRA	SEP = Intact		95% Confidence Interval
Preoperative = PGRA	35.00	14.00	PPV = 71.43	64–74
Preoperative = intact root	2.00	26.00	NPV = 92.86	80–98
	Sensitivity = 94.59	Specificity = 65.00		

PPV, positive predictive value; NPV, negative predictive value; SEP, somatosensory evoked response; PrGRA, preganglionic root avulsion.

matosensory evoked potential recording. Potentials may still be recorded when the posterior rootlet is intact but the anterior rootlet is disrupted. Conversely, the somatosensory evoked potentials may be absent when the posterior rootlet is interrupted, despite an intact anterior rootlet.[5,11]

Direct intradural inspection can provide additional information about the integrity of the anterior and posterior rootlets, but it requires additional surgery through a different surgical approach (i.e., a cervical hemilaminectomy).[5,8,11] Moreover, the anatomical continuity of the rootlets does not necessarily reflect their functional status when examined by intraoperative nerve recording.[6]

The problem of diagnosing functionality of a root avulsion has been addressed in the literature. Celli et al.[11] developed a method for stimulating the nerve root as it exited from the neural foramen with a bipolar electrode while recording the paravertebral muscle response with electromyelography needles. Later, Oberle et al.[5] recorded evoked muscle action potentials from neck muscles in a similar fashion. Their technique involved the simultaneous recording of the cortical somatosensory evoked potential recordings and evoked motor action potentials while stimulating the nerve root at the vertebral foramen. This technique is initially performed without muscle relaxants. In the case of a functionally intact anterior rootlet, the dorsal ramus, which is located a short distance proximal to the stimulation site, is also depolarized by the upward spreading current. Evoked motor action potentials can therefore be recorded in the paravertebral muscles. If a cortical somatosensory evoked potential is recorded positively at the same time, one can tell that the posterior rootlet is functionally intact. In the case of anterior rootlet avulsion, the neck muscles are denervated and evoked motor action potentials are absent. Muscle relaxants are then administered until full muscle relaxation is achieved and the stimulation is repeated. The evoked motor action potentials are lost at that time but the somatosensory evoked potentials can still be recorded.

An alternative approach is to record the motor evoked potential. Turkof et al.[12] introduced a method for recording transcranial electrical motor evoked potentials to evaluate the functional status of the anterior spinal roots and spinal nerves during brachial surgery. These investigators were able to record nerve action potentials from 32 of the 38 nerves that were in continuity and from 21 of 25 nerve stumps. We did not perform motor evoked potential recording, and thus we were unable to test the anterior motor rootlets, relying solely on the dorsal root somatosensory evoked potentials to assess preganglionic root avulsions for both. This leaves open the possibility of an intact dorsal sensory root but an avulsed ventral root. Ventral root grafting has been performed successfully by Carlstedt et al.,[13] who recommend that it be performed early. We would therefore suggest that motor evoked potential recording also be performed to avoid missing the opportunity to provide acute treatment to these avulsions.

Most recently, intraoperative nerve stimulation of the supraclavicular segment of the long thoracic nerve has been recommended by Flores[14] for the evaluation of C5. This relatively simple technique makes use of a peripheral nerve stimulator on the long thoracic nerve above the clavicle and C7. Provided that C6 is also avulsed, there should be no muscle contraction of the serratus anterior on stimulation. This easily available technique is recommended by the author in combination with preoperative computed tomographic myelography.

One weakness of our study is the time point of our multimodality diagnosis being preoperatively. The process of evaluating a brachial plexus is one of incremental information gain, as the clinical examination is backed up by radiology and electromyography, followed by intraoperative inspection and finally intraoperative nerve recording. The surgeon is thus confronted with more information intraoperatively than when examining the appearance of the nerve root directly and will be able to make a macroscopic diagnosis of root avulsion in some cases. This represents more information than that presented in our study. However, even when the root is examined and appears intact perioperatively, functionality cannot be guaranteed. This situation was examined by Oberle et al.[5] They looked at the results of evoked motor action potentials with somatosensory evoked potentials and compared them with the actual appearance of the nerve root dissected out by means of a hemilaminectomy to expose the intradural preganglionic components. They visually inspected both the anterior and posterior rootlets and then tested them by means of somatosensory evoked potentials and evoked motor action potentials, which yielded several instances where the rootlet appeared unharmed but there was no signal. They concluded that these intraoperative nerve recording studies obviated the need for additional exploratory surgery to examine the preganglionic components of the root. These perioperative visual root inspection data represent one step further than our preoperative time point. Using their observational data, we have produced two 4 × 4 contingency tables to examine their intradural in-

Table 4. Two-Way Contingency Table Analysis for Direct Rootlet Inspection versus Evoked Motor Action Potentials*

Intraoperative Visual Diagnosis	EMAP = PrGRA	EMAP = Intact		95% Confidence Interval
Root observed thickened or partly/ completely avulsed	8.00	1.00	PPV = 88.89	64–97
Root normal	2.00	14.00	NPV = 87.5	73–92
	Sensitivity = 80.00	Specificity = 93.33		

PPV, positive predictive value; NPV, negative predictive value; PrGRA, preganglionic root avulsion; EMAP, evoked motor action potential.

Table 5. Two-Way Contingency Table Analysis for Direct Rootlet Inspection versus Somatosensory Evoked Potentials*

Intraoperative Visual Diagnosis	SEP = PrGRA	SEP = Intact		95% Confidence Interval
Root observed thickened or partly/ completely avulsed	9.00	0.00	PPV = 100	76–100
Root normal	5.00	13.00	NPV = 72.22	60–72
	Sensitivity = 64.29	Specificity = 100.00		

PPV, positive predictive value; NPV, negative predictive value; SEP, somatosensory evoked potentials; PrGRA, preganglionic root avulsion.
*Based on Oberle J, Antoniadis G, Kast E, Richter HP. Evaluation of traumatic cervical nerve root injuries by intraoperative evoked potentials. *Neurosurgery* 2002;51:1182–1190.

spection as a test, comparing it with their evoked motor action potentials and somatosensory evoked potential results (Tables 4 and 5). For 25 anterior roots explored, 16 showed no obvious lesion; however, no evoked motor action potentials were elicited in two of these. For the three roots with partial disruption or thickening, evoked motor action potentials produced a signal in one. This uncertainty was more pronounced for the 27 posterior roots explored. Eighteen appeared normal, although somatosensory evoked potentials showed no continuity with the central nervous system in five cases and there was no signal with thickened or partially disrupted rootlets.

CONCLUSIONS

Our study demonstrates that use of intraoperative nerve recording altered the preoperative assessment of root integrity in one-fifth of the intraoperative nerve recording and one-third of the patients. The most useful information was for a positive intraoperative nerve recording result demonstrating conduction through the root. This trend is still seen when intraoperative data from the literature is examined[5] (Tables 4 and 5). These data support that intraoperative nerve recording at least provides additional information to the surgeon during exploratory brachial plexus surgery.

We have assumed that intraoperative nerve recording is the criterion standard for the assessment of nerve function; however, this may not reflect how the nerve normally functions. By this, we mean that just because a nerve or rootlet is seen and tested, and found to have no function during surgery, we cannot rule out the possibility of intraoperative neurapraxia. A negative result may arise from a variety of sources, including immediate local trauma to the axons from the operative dissection, the temperature at the operative site, and the effects of general anesthetic agents. We must thus always remain vigilant for these potential confounding factors both when using intraoperative nerve recording and when reading the literature. It is for this reason that we have focused on the significance of a positive conduction result in this article—those roots that were thought to be avulsed and that intraoperative nerve recording found were intact.

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