Reliability of intraoperative electrophysiological monitoring in selective posterior rhizotomy

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Object. Selective posterior rhizotomy is a well-established treatment for spasticity associated with cerebral palsy. At most medical centers, responses of dorsal rootlets to electrical stimulation are used to determine ablation sites; however, there has been some controversy regarding the reliability of intraoperative stimulation. The authors analyzed data obtained from the McGill Rhizotomy Database to determine whether motor responses to dorsal root stimulation were reproducible.

Methods. A series of 77 patients underwent selective dorsal rhizotomy at a single medical center. The dorsal roots from L-2 to S-2 were stimulated to determine the threshold amplitude. The roots were then stimulated at 2 to 4 times the highest threshold with a 1-second 50-Hz train. A second stimulation run of the entire dorsal root was performed before it was divided into rootlets. Rootlets were individually stimulated and sectioned according to the extent of abnormal electrophysiological propagation. Motor responses were recorded by electromyography and were also assessed by a physiotherapist, and grades of 0 to 4 were assigned. The difference in grades between the first and second stimulation trains was determined for 752 roots.

Statistical analysis demonstrated a clear consistency in motor responses between the two stimulation runs, both in the electromyographic readings and the physiotherapist’s assessment. More than 93% of dorsal roots had either no change or a difference of only one grade between the two trials. Furthermore, the vast majority of dorsal roots assigned a grade of 4 at the first trial maintained the same maximally abnormal electrophysiological response during the second stimulation run.

Conclusions. This study indicates that currently used techniques are reproducible and reliable for selection of abnormal rootlets. Intraoperative electrophysiological stimulation can be valuable in achieving a balance between elimination of spasticity and preservation of underlying strength.

Keywords: cerebral palsy • spasticity • rhizotomy • electrophysiological monitoring • electromyography

Cerebral palsy is primarily a motor function disorder caused by perinatal insults to the developing cerebrum. Selective posterior rhizotomy aims to relieve the ensuing spasticity, which is predominantly seen in the lower limbs, and to improve motor function. In an effort to optimize the balance between elimination of spasticity and preservation of strength, most medical centers rely on intraoperative electrophysiological monitoring based on, or modified from, the original technique described by Fasano and colleagues. Clinically significant improvements in functional outcome have been reported by several groups. Recent evidence has prompted the suggestion that sustained motor responses with significant contralateral and suprasegmental spread are valid criteria for dividing a dorsal rootlet. The usefulness of EMG-guided dorsal rhizotomy in reliably outlining populations of spinal rootlets that are maximally involved in a dysfunctional circuitry and mainte-

Abbreviations used in this paper: CMAP = compound muscle action potential; EMG = electromyography; PT = physical therapy; SPR = selective posterior rhizotomy.
responses, we provide information about the surgical procedure, intraoperative electrophysiological monitoring, lesioning criteria, and multidisciplinary team involvement. We believe this detailed information may encourage standardization of the procedure among medical centers.

Clinical Material and Methods

Patient Population

Data were collected prospectively from the McGill Rhizotomy Database in a series of patients who had undergone SPR at the Montreal Children’s Hospital of the McGill University Health Center since 1991. This continually updated database includes pre- and postoperative evaluations from the neurosurgery, neurology, orthopedic surgery, physiotherapy, and occupational therapy departments. The study population was composed of 77 patients, 30 boys and 47 girls. The patients’ ages at surgery ranged from 2.5 to 8 years, with a median age of 4.3 years. There were 65 patients with diplegia, four with triplegia, and eight with quadriplegia. As part of the informed consent agreement, the patients’ parents allowed us to collect data obtained from electrical stimulation of lumbosacral roots (between L-2 and S-2) for research purposes. Of the 924 lumbosacral roots exposed in 77 patients, 752 dorsal roots (81.4%) were stimulated twice to determine the reproducibility of the electrophysiological response.

Anesthesia Protocol

Anesthesia was induced in all patients by a mixture of sufentanil (0.2–0.5 μg/kg/hr) and propofol (1–10 mg/kg/hr), which was infused along with nitrous oxide. Stimulation began after all infusions had reached a steady state that was maintained throughout the protocol. Secondary tachycardia and hypertension were managed by delaying the stimulation sequence for 5 minutes. A short-acting nondepolarizing neuromuscular blocking agent, rocuronium, was used only at induction. Postoperative analgesia was provided by morphine infusion (4 μg/kg/hr) containing 0.125% bupivacaine. The infusion was continued for 72 hours through an epidural catheter that had been placed under direct vision at the time of surgery.
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**Surgical Procedure**

Patients were placed prone with their hips and shoulders slightly elevated on bolsters. A narrow L1–S2 laminectomy flap was made and the dura opened at midline, thus exposing the cauda equina in its entirety. The spinal levels of the roots were determined by counting from the lowest root in the cul-de-sac by using bone landmarks, size variations of the roots, and by stimulating the motor roots of S-2 and S-1 orthodromically. Electrical stimulation of posterior roots was performed to determine a threshold for a motor response. After the electrophysiological monitoring protocol was completed, the roots were divided into rootlets. Based on their evoked stimulation responses, the rootlets were sectioned using the criteria defined later. The laminotomy flap was then reattached to the surrounding laminae after placement of an epidural catheter for postoperative delivery of analgesic medications.

**Electrophysiological Monitoring**

In all cases, a neurophysiologist, a neurophysiology technician, and a physical therapist were present in the operating room during stimulation. Electrical stimulation of roots and rootlets was performed using two insulated unipolar electrodes (Aesculap, Inc., Bethlehem, PA). The cathode was placed proximally along the course of the dorsal root, and the anode was placed 1 cm distally for orthodromic stimulation. Stimulation of the dorsal roots was accomplished by elevating them from the pool of cerebrospinal fluid, starting on the right side at S-2 and proceeding to L-2. The initial round of stimulations determined the threshold for motor response by using a 1-msec stimulus. The strength of the stimulus was adjusted to provide a maximal dorsal root potential, but care was taken to keep the stimulus intensity low enough to prevent the spread of current to adjacent roots. The highest threshold stimulus intensity for all sensory roots was used as a basis for the intensity of the tetanic stimulus. The entire dorsal root was then restimulated at two to four times the highest threshold intensity with a 1-second 50-Hz stimulus train (Trial 1). The intensity of the current varied from 6 to 15 mA (median 10 mA). For the purpose of this study, a second stimulation run at the same current intensity (Trial 2) was conducted before dividing the posterior root into three to seven rootlets (median four rootlets). The threshold run as well as stimulation Trials 1 and 2 were performed in the same dorsal root sequence: from S-2 to L-2, starting on the right side.

Both the neurophysiologist and the physical therapist assessed the motor responses to electrical stimulation of dorsal roots and rootlets. Recordings of the CMAP were obtained using a multichannel electromyograph (Viking II; Nicolet Biomedical, Inc., Madison, WI) with silver chloride surface electrodes placed bilaterally on the quadriceps, hamstring, and gastrocnemius muscle groups and monitored over a 2-second time frame. Upper-extremity motor responses were recorded either from the deltoid or biceps muscle. Thus, up to eight muscle groups were monitored simultaneously (Fig. 1). The clinical pattern of muscle response was observed and palpated by the physiologist, with particular attention paid to contractions in muscle groups other than those monitored by the neurophysiologist (for example, hip adductors and toe flexors). Rootlets were sectioned based on the extent of abnormality in their clinical and electromyographic motor responses to electrical stimulation.

**Lesioning Criteria**

The response to tetanic stimulation was used to determine which rootlet to cut. The decision to transect or preserve individual rootlets was made on the basis of three kinds of information. The first was the electrophysiological response monitored through the eight-channel recordings. The second criterion was the behavioral response (that is, muscle contraction in the legs) documented by the physiotherapist. Behavioral responses were used to confirm the electromyographic response pattern, to define contractions in unmonitored muscle groups, and to assist with troubleshooting if no electrical response was observed (for example, in rootlets in a refractory period). The final set of criteria included the following: 1) the root level being stimulated (less aggressive lesioning at L-4 and S-2); 2) the number of rootlets severed at previous levels; 3) the strength and quality of evoked responses; and 4) the congruence of the intraoperative information with the clinical status of the patient.

The motor response of each root and rootlet was recorded and assigned a grade of 0, 1+, 2+, 3+, or 4+, as described by Phillips and Park, and also adopted by other authors. This scale is used to grade the response with regard to its level of segmental and contralateral spread and whether it is abnormally sustained. We made a slight modification to the original grading scheme: Grade 0 represented an unsustained response (normal response) and Grade 4+ was assigned to a sustained response with contralateral spread, as well as spread to the upper extremities (Table 1). Therefore, each root stimulation response received a grade for the first and second trial from both the neurophysiologist (EMG Trials 1 and 2) and the physical therapist (PT Trials 1 and 2). Typically, only roots assigned a Grade 4+ response were divided into rootlets. Regardless, some restrictions in the lesioning pattern were carefully observed. In all patients, no more than two thirds of dorsal S-2 rootlets were cut (to preserve knee stability as suggested by Gros, et al.), and sectioning of S-3 and S-4 roots was avoided. Contrary to recommendations given by other authors, the pattern of sustained motor response (for ex-
amples, incremental, multiphasic, or clonic) and H-reflex recovery curves were not used as criteria for rootlet lesioning. The intensity and pattern of clinical and electromyographic motor responses to every stimulation (of roots and rootlets) and decisions regarding sectioning or preservation of individual rootlets were carefully recorded by the neurophysiology technician and ultimately entered into the database.

Postoperative Care and Follow Up

After undergoing rhizotomy, patients were allowed to sit in a chair on the 4th postoperative day. The children received 6 weeks of intensified inpatient rehabilitation devoted to muscle reeducation and strengthening. Thereafter, their rehabilitation continued with standard PT involving stretching and strengthening exercises for the lower extremities. Postoperative stability and control of the lower limbs was further enhanced by judicious use of orthotic devices. All patients underwent assessments preoperatively, at 6 and 12 months postoperatively, and at yearly intervals thereafter.

Statistical Analysis

Paired t-tests were used to determine whether there was a significant shift in the mean response grade between the first and second stimulus for the EMG and PT grade assignments. Simple kappa coefficients were used to determine the degree of correlation between the first and second motor responses. Mantel–Haenszel chi-square testing was used to determine the degree of association between EMG and PT assessments. Finally, t-tests were also used to determine whether there was a difference between the lesioning rate of rootlets assigned a grade of 4+ and the overall rootlet lesioning rate. An error probability not exceeding 5% was considered significant.

Results

Grading of Motor Responses

For both stimulation trials, the number of roots in each EMG and PT grade is shown in Table 2. In all subjects combined, the mean of the assigned grades (0–4+) for the first and second trials was the same for both EMG (3.2 and 3.3, respectively; that is, between Grades 3+ and 4+) and PT groups (3.1 and 3.2, respectively). Paired t-test analysis demonstrated no significant shift in the mean response between Trials 1 and 2 in either the EMG or PT group. Table 2 shows that the majority of all twice-stimulated dorsal roots had an electrophysiological response designated Grade 3+ or Grade 4+ in the EMG (mean 78.9%) and PT (mean 75.3%) groups, respectively. In the 77 procedures performed, roots were divided into several rootlets according to the size of the dorsal lumbosacral root. On average, 51.2% of these dorsal rootlets were transected in each procedure. This is in keeping with the number of roots to which Grade 4+ was assigned by the electromyographer (mean 46.5%) and the physiotherapist (mean 44.4%).

Reproducibility of Motor Responses

The grade differences between Trials 1 and 2 for both EMG and PT groups were determined for the 752 dorsal roots in 77 patients. Figure 2 shows the number of roots in each category (0 = no change, −1 = decrease by one grade, +2 = increase by two grades, and so forth). In the EMG group, only 51 (6.8%) of the 752 roots exhibited a difference of two or more gradations. Similarly, on the second stimulation trial in the PT group, 54 roots (7.2%) were assigned a grade that was two grades above or below the initial assignment. In contrast, more than two thirds of the nerve roots in both the EMG and PT groups maintained the same grade level between the first and second trial (Fig. 2 upper left). The absolute change in response grade (± 1, ± 2, and so forth) between the first and second stimulus of an individual root ranged from 0 to 3 (Fig. 2 upper right). The overall mean response grade change was not significantly different (EMG 0.41; PT 0.43; that is, less than ± one grade difference). Thus, 93.1% of all 752 roots had no change or differed by only one gradation in both groups. This absolute grade difference between trials did not vary among individual patients. A simple kappa coefficient for correlating the response grade in the first trial with the response grade in the second demonstrated good agreement between trials for both the EMG (κ = 0.675 at α = 0.05) and PT groups (κ = 0.659 at α = 0.05).

Grade 4+ Motor Responses

We first looked at all roots assigned the maximally abnormal response of Grade 4+ in Trial 1. Figure 2 lower left shows that of the 324 dorsal roots with a grade of 4+ in EMG Trial 1, 268 (82.7%) maintained a response grade of 4+ in the second trial, whereas 44 (13.6%) were assigned a grade of 3+. Similarly, 248 (77.0%) of the 322 roots assessed by the physical therapist were given a grade of 4+ in both trials. Only 11 roots (3.4%) from the EMG group and 19 (5.9%) from the PT group varied by two grades or more. We then looked at roots assigned a grade of 3+ in the first stimulation run. Figure 2 lower right demonstrates that of the 242 dorsal roots assigned a grade of 3+ in EMG Trial 1, 152 (62.8%) kept the same grade in the second run, whereas 131 (59.3%) of the 221 nerve roots in the PT group were given a grade of 3+ in both trials. Note that more than 30% of these Grade 3+ nerve roots (EMG 31.8%; PT 32.6%) were assigned the highest grade (4+) after the second stimulation train. Given that rootlets assigned a grade of 4+ (that is, a sustained response with contralateral and suprasegmental spread) would likely be selected for sectioning, and that rootlets with grades of 0, 1+, and 2+ would certainly be spared,
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nearly one third of all roots assigned a grade of 3+/H11001 in the first trial would have been divided based on a 4+/H11001 response in the second trial. Finally, as shown in Fig. 2 upper, very few roots (< 7% on average) differed by two grades or more. It is therefore unlikely that roots assigned grades of 1+ or 2+ in Trial 1 would become Grade 4+/H11001 in Trial 2.

Rootlet Lesioning Rates
A clear correlation was also demonstrated between the EMG and PT groups. This was determined using Mantel–Haenszel chi-square analysis, which did not reveal a significant difference (p = 0.475) between the evoked motor responses recorded by the neurophysiologist and those assessed by the physical therapist. Finally, t-tests confirmed that the lesioning rate for rootlets from roots assigned a grade of 4+ was significantly higher (65.4–80.2%, mean 75.4%) than the overall lesioning rate (mean 51.2%; Fig. 3).

Discussion

Historical Background
Selective dorsal rhizotomy for the relief of debilitating spasticity in carefully selected children has undergone numerous refinements over the past decades. Foerster9 first proposed intraoperative electrical stimulation to identify the segmental level and distinguish between ventral and dorsal roots. In the 1960s, Gros and colleagues,10 in an attempt to limit the motor and sensory side effects, incorporated EMG into the procedure to permit identification of rootlets innervating more dysfunctional muscle groups. Subsequently, Fasano, et al.,8 developed a series of criteria based on the abnormality of evoked motor responses to electrical stimulation. Later, Peacock and Arens24 moved the operative site to the lumbosacral canal, allowing a more positive identification of the segmental level. Most surgeons continue to use variations of the methods originally described by Fasano, Peacock, and colleagues.
Concerns About Intraoperative Monitoring

Although sphincteric complications from SPR are now much reduced to acceptable levels, several groups have challenged the reliability of intraoperative electromyographic monitoring in defining populations of rootlets that are maximally involved in the maintenance of spasticity.

Rationale Underlying Selectivity of Posterior Rhizotomy

Since the landmark studies published by Sherrington, our understanding of the mechanisms of spasticity has evolved considerably. Current concepts underlying SPR are derived from the initial experimental work in cats. It was postulated that lumbosacral dorsal rootlets that evoke abnormal reflex activity in lower-extremity muscles on direct, repetitive, high-frequency stimulation are involved in a dysfunctional spinal reflex. These abnormal rootlets should therefore be selected for sectioning. Similarly, dorsal rootlets with normal reflex responses must be spared because they presumably do not participate in the abnormal circuitry. We advocate the routine use of intraoperative electrophysiological monitoring during SPR. By selectively lesioning the posterior rootlets involved in the spastic process, we have obtained significant reduction of spasticity coupled with preservation of sensation, voluntary muscle control (Mittal, et al., unpublished data), and bladder function. In an attempt to preserve sphincter control, several groups have recently tried to identify pudendal afferents more accurately. In our experience, in addition to identifying pathological reflex circuits for interruption, EMG-guided rhizotomy also enables accurate identification of sacral nerve roots involved in bowel and bladder control. It remains critical to limit lesioning of dorsal S-2 rootlets and to avoid sectioning S-3 and S-4 roots during SPR.

Consistency of Electrophysiological Responses

Using the criteria of Steinbok, et al., for contralateral and suprasegmental spread as the primary lesioning parameter both with EMG and PT assessments, we show that evoked responses to electrical stimulation are consistent, reproducible, and consequently very reliable. As seen in Fig. 2 other, only a minority of nerve roots varies by more than one grade between Trials 1 and 2. If the decision to divide a sensory root into rootlets depends on a root achieving Grade 4+ spread in one of the trials, the probability of a Grade 4+ response normalizing to a Grade 0, 1+, or 2+ is minimal (3.4% and 5.9% by EMG and PT assessment, respectively; Fig. 2 lower left). Furthermore, if we accept that in more than 90% of cases, roots either do not change grade or move by only one grade, and that more than 30% of roots assigned a Grade 3+ response will change to a Grade 4+ response on a second trial, then the technique is certainly reliable enough to dispense with restimulation of roots that are either Grade 4+ or Grades 0, 1+, or 2+ during the first run. To optimize lesioning, only roots with Grade 3+ responses in the first stimulation trial should be restimulated. This is because a significant proportion of Grade 3+ roots was assigned the highest grade at the second stimulation trial. Transient refractoriness of the root may possibly explain this phenomenon. Figure 4 outlines our proposed intraoperative electrophysiological monitoring scheme.

Implications of Root Stimulation Reliability for Rootlet Sectioning

In this study we demonstrate significant reliability of the motor response at the root level. The rootlets themselves were not stimulated twice. Nonetheless, the incomplete correlation between the rate of Grade 4+ responses on EMG and PT assessment (mean 45.4%) and the overall rootlet lesioning rate (51.2%) indicates that rootlet stimulation had an impact on the final sectioning decision. In fact, looking only at roots with Grade 4+ responses, the
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Areas of Criticism and Concern

Conclusions

Contrary to previous reports, in this study we clearly demonstrate that motor responses obtained by repetitive orthodromic stimulation of posterior roots are consistent and easily reproducible by both EMG and PT assessments. Obviously, more work is needed to refine our understanding and ability to monitor responses and, hence, target our sectioning. No study has definitively shown that intraoperative monitoring is superior to random rootlet lesioning. In this patient population, a significant proportion of roots produced maximally abnormal motor responses. One could therefore envisage doing without intraoperative electrical stimulation to reduce spasticity. Nonetheless, we are confident that, in this era of intraoperative functional navigation and monitoring, careful analysis of appropriate selection outcome measures (especially those looking at
enhancement of function rather than elimination of spasticity) will allow the selective procedure to become the standard of care. We hope that this study will encourage further investigations and establishment of uniform paradigms for centers in which SPR is used.

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