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Relationship of intraoperative electrophysiological criteria to outcome after selective functional posterior rhizotomy

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At British Columbia's Children's Hospital, the criteria used in selective functional posterior rhizotomy (SFPR) evolved in three distinct phases. In Phase 1 the electrophysiological criteria for abnormality included a low threshold to a single stimulation, a sustained response to 50-Hz stimulation, and spread outside the segmental level being stimulated. In Phase 2 the electrophysiological criteria were unchanged, but fewer L3–4 nerve roots were cut. In Phase 3, fewer L3–4 nerve roots were cut, as in Phase 2, but based on the results of posterior nerve root stimulation in nonspastic controls, the only electrophysiological criterion used was contralateral and suprasegmental spread. The present study examined the relationship between the criteria used in each phase and patient outcome.

The records of 77 consecutive children who underwent SFPR and had a minium follow-up period of 1 year were reviewed, comprising 25, 19, and 33 patients in Phases 1, 2, and 3, respectively. Outcome parameters included quantitative assessments of lower-limb spasticity and range of motion, and qualitative assessments of lower-limb function.

In Phase 3, 52% of the nerve roots were cut, compared to 66% in Phases 1 and 2. In all three phases there was a significant decrease in lower-limb spasticity and an increase in range of movement, with the smallest decrease in spasticity in Phase 3. Over 90% of children in each phase improved with respect to lower-limb function, and excluding independent walkers and quadriplegics confined to a wheelchair, improvement in the level of ambulation occurred in 87.5%, 71.4%, and 73.7% of patients, in Phases 1, 2, and 3, respectively.

KEY WORDS • selective posterior rhizotomy • cerebral palsy • spasticity • electrophysiological criteria

SELECTIVE functional posterior rhizotomy (SFPR) is a well-established treatment for spasticity associated with cerebral palsy, and favorable results have been reported from a number of different centers.[1,8,9,14–16,19,21] The procedure is based on the concept that one can define, by the responses to intraoperative electrical stimulation, populations of rootlets within the posterior nerve roots that are maximally involved in the maintenance of spasticity.[8] The original electrophysiological criteria used to define a posterior nerve rootlet that should be divided in SFPR, and the criteria that were used in our center initially, included: 1) a low threshold to a single stimulus, 2) a sustained response to a 50-Hz tetanic stimulus, and 3) diffusion of the response to muscle groups not involved in the rootlet's segmental distribution.[8,14]

An analysis of the responses to posterior nerve root stimulation in children without spasticity who were undergoing laminectomies for spinal cord untethering demonstrated that the original electrophysiological criteria were not necessarily indicative of the posterior nerve rootlets involved in the spastic process.[17–19] As a result of these findings, the electrophysiological criteria used to determine which posterior rootlets to divide in SFPR were altered. The only electrophysiological criterion used to indicate rootlets that might be involved in the spastic process was the extent of spread outside the rootlet's segmental distribution, to the contralateral lower limb or suprasegmentally into the upper limb, neck, and/or face.

The purpose of this study was to compare the population of patients who had undergone SFPR in the initial phase, using the original electrophysiological criteria, with those in the latter phase, using the modified criteria, to determine whether there was a difference in the extent of transection of each posterior root, and whether there was a difference in patient outcome.

Clinical Material and Methods

Patient Population

The records of the first 77 children with cerebral palsy who underwent SFPR at British Columbia's Children's Hospital were reviewed. The factors analyzed were information describing the electrophysiological and other criteria used to determine which posterior nerve rootlets to divide, the percentage of each nerve root that was divided during the procedures, and clinical outcome.

The 77 children in the study ranged in age from 2.2 to 18.1 years, with a mean of 5.7 years. Forty-three patients were spastic diplegic, 33 were spastic quadriplegic, and one patient was triplegic.

In Phase 1 (first 25 patients), the age at surgery ranged from 2.7 to 16.4 years, with a mean of 5.4 years. Sixteen patients were spastic diplegic and nine were quadriplegic. In Phase 2 (next 19 patients), the age at surgery ranged from 2.2 to 18.1 years, with a mean of 6.8 years. Ten children were spastic diplegic, eight were quadriplegic, and one was triplegic. In the final phase (33 patients), the age at surgery ranged from 2.5 to 12.3 years, with a mean of 5.4 years. There were 17 spastic diplegics and 16 quadriplegics.

Operative Procedure

With the patient prone, L-1 to S-1 laminectomy was performed as described by Cochrane and Steinbok.[5] The nerve roots of the cauda equina were exposed. The individual nerve roots were identified, and the posterior root was separated from the anterior root close to the exit foramen for the root. In the first seven cases, the procedure involved the L-2 to S-1 nerve roots, but thereafter the S-2 roots were also included.

Each posterior nerve root was subdivided into three to six rootlets, each of which was stimulated using two unipolar electrodes (Aesculap Surgical Instruments, Burlingame, CA). No particular attention was paid to whether the cathode or anode was the proximal electrode, and the distance between the two electrodes was not fixed but ranged from 5 to 12 mm. A constant-voltage square-wave stimulator (model SD9, manufactured by Grass Instruments, Quincy, MA) was used, with a stimulus intensity varying from 10 to 100 mV, a stimulation duration of 0.1 msec, and a delay time of 0.01 msec using a biphasic stimulus output. The response threshold was defined as the stimulus intensity at which the first muscle contraction was visibly noted in the segmental distribution of the posterior nerve rootlet or root being stimulated. Tetanic stimulation at 50 Hz was then applied for 1 second at the threshold level of stimulation, and the nerve rootlets were cut or saved depending on the responses.

Recordings were made in the first 28 patients using needle electrodes in the gastrocnemius and vastus medialis muscles (17 patients) or gastrocnemius, vastus medialis, and tibialis anterior muscles (11 patients). In the next 16 children, recordings were made using Ag–AgCl electrodes applied over the bellies of the hip adductor, vastus medialis, tibialis anterior, and gastrocnemius muscles bilaterally. In the most recent 33 patients, surface electrodes were also placed over both deltoid and extensor digitorum communis muscles in the upper limbs, and the sternocleidomastoid and masseter muscles on one side, depending on the side to which the head was turned, so that suprasegmental spread could be assessed.

In the first 28 patients the responses were recording using an electromyographic (EMG) evoked potential device. Thereafter, a 17-channel electroencephalograph was used, and a printout of the responses was made (Neuropack 4 evoked potential device and electroencephalograph manufactured by Nihon-Kohden, Irvine, CA).

Anesthesia was induced intravenously, and after intubation with succinyl choline, light general anesthesia was maintained with a volatile agent and a narcotic. No neuromuscular blocking agents were used after intubation.

Changes in the Selection Process

The criteria for determination of which nerve rootlets to cut evolved during the period of the study in three distinct phases.

Phase 1. In the first 25 patients nerve rootlets were considered to be involved in the spastic process if they met one or more of the following criteria: 1) a low threshold to a single stimulus, 2) a sustained response to 50-Hz tetanic stimulation at a threshold level (a sustained response was a response that persisted for the duration of the 50-Hz stimulation, regardless of the pattern of response), or 3) spread of the response to muscle groups in the lower limbs, outside the distribution of the nerve rootlets being stimulated. The criterion that was relied on most frequently was the presence of a sustained response to tetanic stimulation at 50 Hz, with the threshold being used as a secondary differentiator. The degree of spread was considered to be the least discriminating criterion.

Phase 2. In the next 19 patients the electrophysiological criteria remained unchanged, but a conscious decision was made to save more of the L-3 and L-4 nerve roots in an attempt to decrease the degree of quadriceps muscle weakness that was noted in the first 6 weeks postoperatively.

Phase 3. In the last 33 patients the electrophysiological criteria for selection of nerve rootlets to be cut were changed. The only criterion used was the extent of response spread to the contralateral lower-limb muscles and to the muscles of the upper limb, neck, and face. The presence of a sustained response to 50-Hz stimulation, and the threshold at which the response occurred, were ignored. The deliberate effort to spare more of the L-3 and L-4 nerve roots continued.

Assessment of the Extent of the Posterior Nerve Root Division

During the operative procedure, when the surgeon had completed the transection of posterior nerve rootlets at any particular level, a visual estimate was made by the surgeon and the assistant of the percentage of the nerve root divided. No formal study of the accuracy of this visual estimate was performed, but in a few patients the surgeon and assistant independently estimated the percentage of the nerve root cut, and there was good concordance between the two observers, with no more than a 5% difference. This value for the percentage of the posterior root transected was documented and was reviewed retrospectively as part of this study.

Outcome Assessments

Outcome measures included the degree of spasticity, strength of the quadriceps muscle, and range of motion. Spasticity of the adductor, hamstring, and plantar flexor muscles was assessed using the Penny and Giles myome-

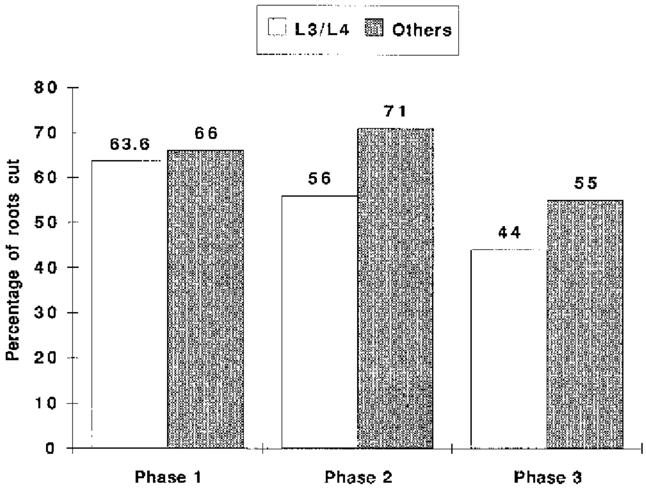

FIG. 1. Bar graph showing the average percentage of posterior nerve roots cut at L3–4 and at all other levels combined in each of the three phases of the study. In Phases 2 and 3, a decision was made to cut fewer L-3 and L-4 nerve roots. In Phase 3, the electrophysiological criteria for functional selection were changed.

ter, a force transducer that measures the force required to overcome the resistance of the muscle tone while moving the joint through the range of motion. The mean force, measured in kilograms, was recorded from five trials for each muscle group. These trials were performed in every case by the same rater, who was aware of the patient's operative status but was blind to the results of the previous myometry test.

The strength of the quadriceps muscle was assessed using the myometer to measure the force, in kilograms, generated by voluntary contraction of the muscle, and again the mean of five measurements was recorded.

Myometry was performed after carefully assessing the passive range of motion of hip abduction in extension, knee extension with the hip at 90°, and ankle dorsiflexion, to avoid pushing against a fixed contracture. The myometer head was placed in a standard location, namely: above the medial condyle for testing hip adductor muscle spasticity; on the heel cord, with the bottom edge just above the os calcis, for testing hamstring muscle spasticity; on the plantar surface of the foot, over the heads of the metatarsal bones, for testing ankle plantar flexor muscle spasticity; and on the anterior aspect of the ankle immediately proximal to a line between the malleoli, for testing quadriceps muscle strength. For each muscle group tested, positioning of the limb was standardized, and passive movement of the joint was performed at a standardized velocity of 4 sec/excursion when assessing spasticity of the hip adductor and hamstring muscles, and 3 sec/excursion for assessing the ankle plantar flexors.

Intrarater reliability was tested on 16 children with spasticity (27 legs), and intraclass correlation coefficients that varied between 0.84 and 0.99 were obtained (A Reiner, *et al.*, unpublished data). Acceptable reliability with the use of the myometer has been reported previously in studies of spasticity in elbow flexor and ankle plantar flexor muscles in adults with central nervous system dysfunction[11] and in ankle plantar flexor muscles in children with cerebral palsy.[7]

TABLE 1
Percentage of posterior nerve roots cut

Study Group	Posterior Nerve Root Transection (%): Spastic Quadriplegic Patients	Posterior Nerve Root Transection (%): Spastic Diplegic Patients	Statistical Analysis (t-test)
Phase 1	68.1	65.0	t = 1.75, p = 0.09
Phase 2	68.5	64.7	t = 1.75, p = 0.09
Phase 3	56.6	47.4	t = 2.84, p = 0.008

Passive range of motion was measured with a goniometer using standardized anatomical landmarks and the methods proposed by the American Academy of Orthopedic Surgeons.[3]

Functional outcome was assessed with respect to locomotion, seating, and other changes noted outside the lower limbs. This information was obtained by talking to the patient, parents or guardians, or other caregivers, and by direct examination by a neurosurgeon, orthopedic surgeon, and physiotherapist. In the patients examined most recently, formal assessments of upper-limb function were performed by an occupational therapist.

Data Analysis

Data were coded and entered on a desktop computer and analyzed using commercially available software. Means were compared with a t-test or a one-way analysis of variance (ANOVA) plus Tukey's B multiple comparison test. Proportions were compared with a chi-square test. Statistical significance was chosen as $p < 0.05$.

To minimize the chance of a false positive conclusion, two clinically important outcomes were chosen *a priori* for the primary analysis. For the extent of spasticity, hip adductor muscle spasticity was chosen as the primary outcome measure because, of the three muscle groups tested, it is usually the most representative of the overall degree of spasticity and it is functionally significant. For range of movement, range of the hip abductor muscles was selected for primary analysis, because this range is related to hip adductor muscle spasticity and is functionally significant.

Results

One patient died 4 months postoperatively from myocarditis unrelated to the operative procedure. The remaining 76 patients all were followed postoperatively for 12 to 60 months, with a mean of 25 months.

Amount of Posterior Nerve Root Division

The total amount of posterior nerve root division in each patient was calculated as the mean of the percentage cut at all levels on both sides. In Phase 3, 52% of the posterior nerve roots were cut, compared to 66% in both Phases 1 and 2 (ANOVA, $p < 0.0001$).

Phase Differences. Because there was a conscious decision after the first 25 patients (Phase 1) to spare more of

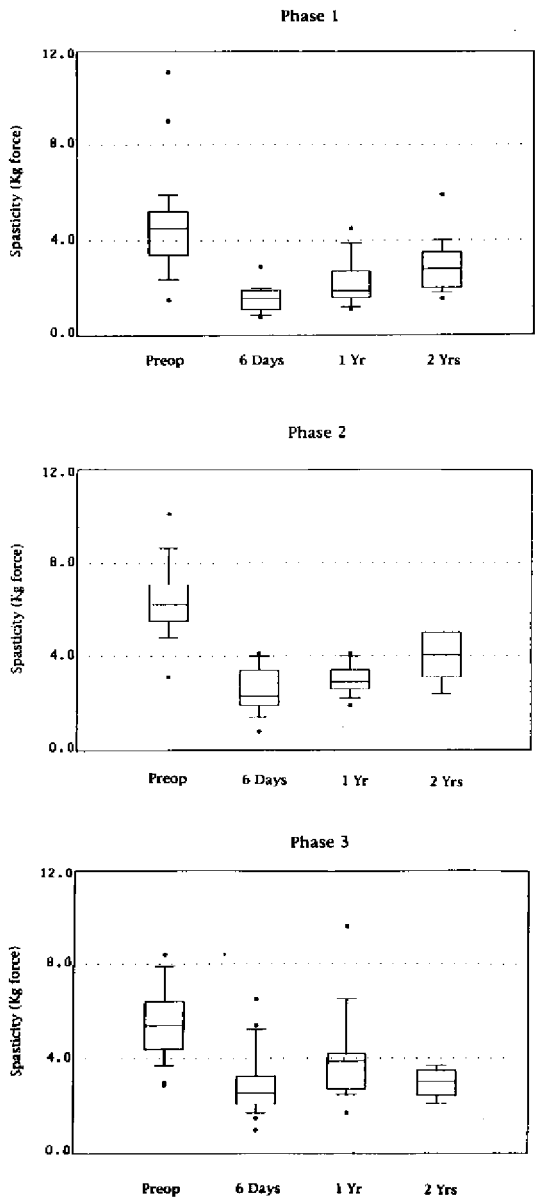

FIG. 2. Box and whisker plots showing the degree of hip adductor muscle spasticity as assessed using the myometer before and after selective functional posterior rhizotomy for patients in Phase 1 *(upper)*, Phase 2 *(center)*, and Phase 3 *(lower)*. Each *box* defines the interquartile range, the *line* in each box represents the median, and the *vertical bars* represent the 5th and 95th percentile values.

the L-3 and L-4 posterior nerve roots, these were analyzed separately from the remaining nerve roots for the purpose of determining the amount of posterior nerve root transection during the different phases. The average amount of L-3 and L-4 posterior nerve root division was 64% for Phase 1, versus 56% and 44% in Phases 2 and 3, respectively (Fig. 1) (ANOVA, $p < 0.0001$) with all phases being different from each other. For all nerve roots except L-3 and L-4, the average amount cut was 66% in Phase 1, 71% in Phase 2, and 55% in Phase 3 (Fig. 1) (ANOVA, $p < 0.0001$) with Phase 3 different from Phases 1 and 2 (Tukey's B test).

TABLE 2
Mean outcome measurements

Outcome Parameter	Baseline (Preop)	1 Yr Postop	Statistical Analysis (t-test)
spasticity of hip adductor muscles (force in kg)	5.22	2.89	$t = -8.32$, $p < 0.001$
range of motion of hip abductor muscles (degrees)	20.60	41.48	$t = 11.22$, $p < 0.001$
strength of quadriceps muscles (force in kg)	4.75	6.15	$t = 2.72$, $p = 0.02$

Diplegics Versus Quadriplegics. An analysis was performed to determine whether there was any correlation between the amount of posterior nerve root transection in children who were spastic diplegic versus quadriplegic. In Phases 1 and 2, there was no significant difference between the diplegic and quadriplegic populations in the percentage of posterior nerve roots cut, but in Phase 3 a smaller percentage of nerve roots was transected in diplegics than in quadriplegics (Table 1).

Extent of Spasticity

Lower-limb spasticity, as quantified using the handheld myometer, was decreased after SFPR in all three phases of the study in all muscle groups tested, namely the hip adductor, hamstring, and ankle plantar flexor muscles, and this result was maintained throughout the follow-up period. The mean change in spasticity after SFPR in each of the three phases of the study is shown in Fig. 2 for the hip adductors: the muscle group chosen for primary analysis. The patterns of change for the hamstring and ankle plantar flexor muscles were similar. For all patients combined, the spasticity of the hip adductors was significantly decreased at 1 year postoperatively compared to preoperatively ($t = -8.32$, $p = < 0.001$) (Table 2).

To allow comparisons between the three phases of the study, the change in spasticity from the preoperative baseline value to that at 1 year postoperatively was expressed as a percentage of the baseline value. The decrease in spasticity at 1 year after SFPR showed no difference between Phases 1 and 2 or Phases 2 and 3, but there was a significantly smaller decrease in spasticity in Phase 3 compared to Phase 1 (ANOVA, $p = 0.03$, Tukey's B test) (Table 3).

Scatterplots were drawn to examine the relationship between the extent of the reduction in spasticity at 1 year after SFPR and the total amount of posterior nerve root transection. There was no correlation among the percentage of posterior nerve roots cut and the decrease in spasticity in the hip adductor muscles at 1 year after SFPR for spastic diplegics, or quadriplegics in the whole study group (Fig. 3), or for patients in any individual phase of the study.

Range of Motion

The range of motion in the lower-limbs improved significantly following SFPR in all phases of the study in all muscles tested, namely the hip abductors, the knee extensors, and the ankle dorsiflexors. The mean change in range

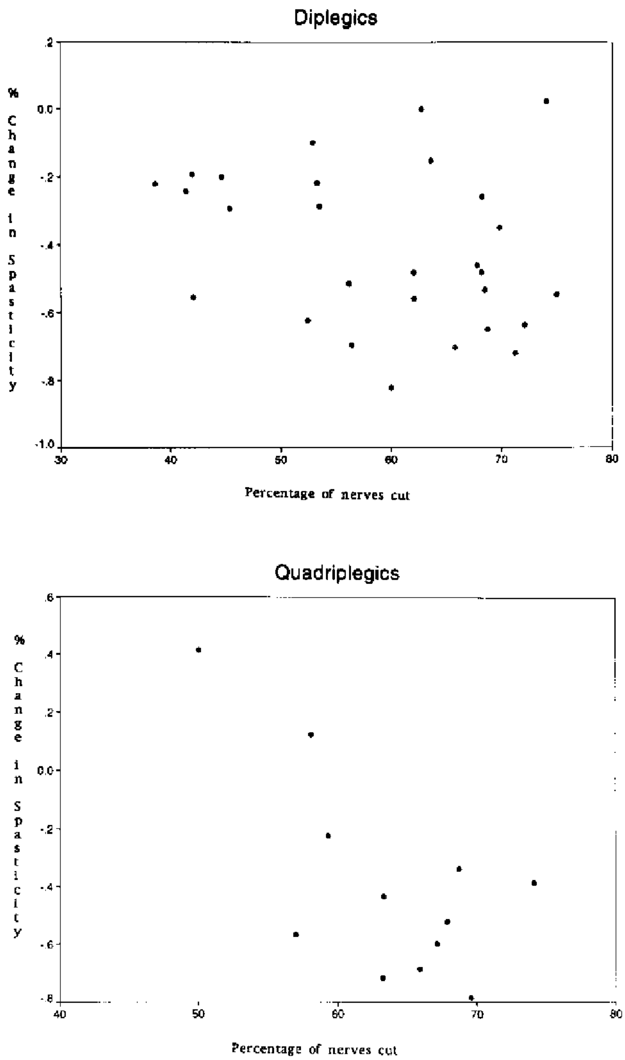

FIG. 3. Scatterplot graphs showing the percentage change from baseline (0.0) in hip adductor muscle spasticity as measured by myometry 1 year postoperatively, for spastic diplegic *(upper)* and spastic quadriplegic *(lower)* patients. A negative value indicates a reduction in spasticity. The scatterplot is based on 40 patients in the study who underwent assessment of hip adductor muscle spasticity using myometry both preoperatively and at 1 year postoperatively.

of motion after SFPR in the three phases of the study is shown in Fig. 4 for the hip abductor muscles, movement of which was chosen for primary analysis. The patterns of change for the knee extensor and ankle dorsiflexor muscles were similar. The mean range of motion of the hip abductors for all patients combined was significantly increased at 1 year postoperatively compared to preoperatively ($t = 11.22$, $p = < 0.001$) (Table 2).

To allow comparison among the three phases of the study, the change in range of motion from the preoperative baseline value to that at 1 year postoperatively was expressed as a percentage of the baseline value. For the hip abductors, the muscle group chosen for statistical analysis, there was no significant difference among the three phases of the study (Table 3).

TABLE 3

Mean percentage changes in spasticity, range of motion, and muscle strength at 1 year postoperatively

Outcome Parameter	Phase 1	Phase 2	Phase 3	Analysis of Variance
change in hip adductor muscle spasticity (%)	−47.50	−48.60	−24.70	p = 0.03
change in hip abductor muscle range of motion (%)	104.00	125.00	77.00	p = 0.93
change in strength of quadriceps muscle (%)	29.00	30.00	22.00	p = 0.74

Muscle Strength

The strength of the quadriceps femoris muscle, as measured using a myometer, sometimes decreased immediately postoperatively, especially in Phase 1, but by 1 year later mean quadriceps strength had returned to or exceeded the baseline value (Table 2). The mean percentage change in quadriceps muscle strength at 1 year from the preoperative level was similar in all three phases (Table 3).

Functional Outcome

The functional outcome with respect to the lower limbs was considered in two ways. First, patients were categorized as having improved sitting or locomotion if the child's sitting and/or ability to get around was favorably influenced by rhizotomy in the opinion of the parent and/or treating physiotherapist. Using this definition, functional improvement was noted in 92%, 95%, and 93% of children in Phases 1, 2, and 3, respectively.

Second, patients were said to have an improved level of locomotion if they changed from one level of locomotion to a better level according to the scale in Fig. 5. This scale does not detect improvement in the level of locomotion in patients who were walking independently before surgery, because they already have the maximum possible score. It is also unlikely to detect the changes that one might reasonably expect from SFPR in patients who were wheelchair-dependent spastic quadriplegics preoperatively. These two groups of patients were therefore excluded from the analysis of data on this scale. Among the remaining patients, improvement occurred in 14 of 16 patients (87.5%) in Phase 1, 10 of 14 (71.4%) in Phase 2, and 14 of 19 (73.7%) in Phase 3, and there was no significant difference between the three phases (chi square = 1.37, $p = 0.50$).

Suprasegmental Effects

Suprasegmental changes were noted by the caregivers in 22 of 24 living patients (92%) in Phase 1, 16 of 19 patients (84%) in Phase 2, and 23 of 33 (70%) in Phase 3. Improvement in the upper limbs, characterized by less spasticity, more function, and/or more range of movement, was the most common finding and occurred in 75% of patients with some upper-limb involvement in Phase 1, and in 74% in both Phases 2 and 3. The other relatively common suprasegmental changes included improved speech, with better breath control, and sitting straighter with the head less flexed.

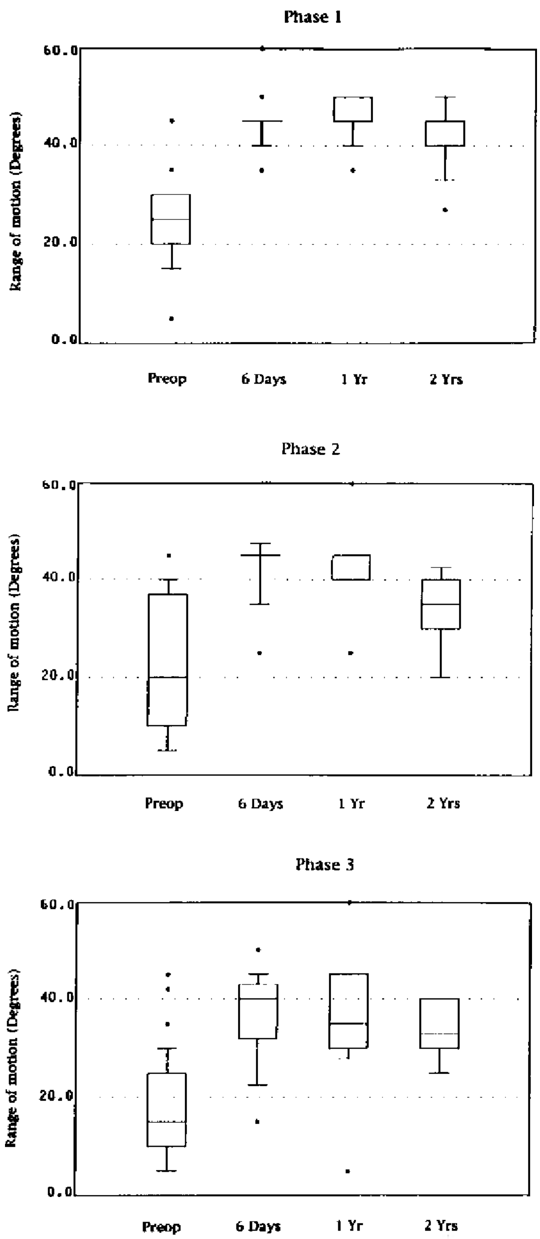

FIG. 4. Box and whisker plots showing the range of motion of the hip abductor muscles before and after selective functional posterior rhizotomy for patients in Phase 1 *(upper)*, Phase 2 *(center)*, and Phase 3 *(lower)*. Each *box* defines the interquartile range, the *line* in each box represents the median, and the *vertical lines* represent the 5th and 95th percentile values.

Postoperative Outcome

	Preoperative status	Total	Wheelchair	Commando crawl	Crawl	Stand	Walk walker	Walk crutches	Walk
P	Wheelchair	4*	2				1		
h	Commando crawl	6					6		
a	Crawl	5				1	4		
s	Stand								
e	Walks with walker	4					1		3
	Crutches/canes	1						1	
1	Walk independent	5							5
	* 1 died								

Postoperative Outcome

	Preoperative status	Total	Wheelchair	Commando crawl	Crawl	Stand	Walk walker	Walk crutches	Walk
P	Wheelchair	2	1	1					
h	Commando crawl	4		1			3		
a	Crawl	5					4	1	
s	Stand								
e	Walks with walker	4					3	1	
	Crutches/canes	1							1
2	Walk independent	3							3

Postoperative Outcome

	Preoperative status	Total	Wheelchair	Commando crawl	Crawl	Stand	Walk walker	Walk crutches	Walk
P	Wheelchair	8	7				1		
h	Commando crawl	7	1	2	1		3		
a	Crawl	3					1	1	1
s	Stand								
e	Walks with walker	8					2	3	3
	Crutches/canes	1							1
3	Walk independent	6							6

FIG. 5. Chart showing functional status according to the level of ambulation preoperatively and at the last follow-up examination after selective functional posterior rhizotomy for patients in each of the three phases of the study. Patients who improved in their level of ambulation are shown above the *shaded bars*.

Neurological Complications

Permanent sensory loss occurred in one patient in Phase 1, in the form of a mild decrease in all modalities of sensation in the L-5 and S-1 dermatomes on one foot. Urinary dysfunction, typically characterized by increased episodes of incontinence in children who had been incompletely toilet trained preoperatively, was noted in four children in Phase 1, one in Phase 2, and three in Phase 3. In one child in Phase 3 the change in urinary function was still present 2 years postoperatively, but in the other seven children urinary function returned to the baseline level by 3 months after surgery, and in none of these patients was catheterization required after discharge at 6 days postoperatively. All children in whom urinary complications occurred had a minimum of 50% of each S-2 root cut. There was no correlation between the incidence of neurological complications and whether the patient was in Phase 1, 2, or 3.

Discussion

The concept underlying SFPR for treatment of spasticity in the lower limbs came from experimental work in cats, in which it was demonstrated that repetitive orthodromic stimulation of posterior nerve roots caused reflex depression of spinal motor neurons as the rate of stimulation increased from 10 to 50 Hz.[6] It was postulated that this inhibitory activity was related to normal presynaptic inhibition. Fasano, *et al.*,[8] suggested that similar responses might be normal in humans and that lack of inhibition in spastic patients might lead to different, less inhibited responses to posterior nerve root stimulation. If indeed this was the case, then it might be possible to differentiate, based on the results of intraoperative stimulation, among those posterior nerve rootlets involved in the spastic process, those that were not, and those that were, although to a lesser degree. By cutting the involved rootlets and preserving the uninvolved ones, spasticity might be relieved while preserving sensory function.

Electrophysiological Criteria

Fasano, *et al.*,[8] reviewed their results of electrical stimulation of posterior nerve rootlets in children with spastic diplegia and subdivided the responses into three distinct groups. In the first situation, repetitive stimulation of the nerve rootlet at frequencies of 30 to 50 Hz produced a muscular contraction only with the first stimulus and, thereafter, there was relaxation during the remainder of the stimulation period. Stimulation of these nerve rootlets caused contraction only in one or two muscle groups in the ipsilateral limb. These rootlets were believed to be inserted in spinal circuits having normal inhibitory activity and were thus believed to be normal. A second population of nerve rootlets could be identified in which the response to repetitive stimulation at 30 to 50 Hz was a sustained and synchronous activation of muscles. There was often abnormal activation of other circuits, such that there was spread of the muscle response to the contralateral lower limb, the upper limbs, or even the trunk and neck muscles. It was believed that these nerve rootlets were projecting to spinal circuits in which the normal inhibitory processes were lacking and that they were therefore involved in the maintenance of spasticity. This latter group of nerve rootlets would be candidates for transection in an attempt to relieve spasticity. A third response observed in some cases was an excess of inhibition, which was often corrected by sectioning an adjacent nerve root in which inhibition was lacking.

Peacock and Arens,[14] who modified the procedure of selective functional rhizotomy described by Fasano, *et al.*,[8] indicated that the posterior nerve rootlet being stimulated was divided if it had "a low threshold, was associated with a sustained muscular contraction or with diffusion of contraction to muscle groups not belonging to that rootlet's segmental distribution. If the rootlet had a high threshold, if the muscle's duration of contraction was brief and diffusion of contraction did not occur, that rootlet was left intact."[14] The electrophysiological criteria that we used initially (Phases 1 and 2) were those described by Peacock and Arens. A sustained response, which was defined as an EMG response that persisted for the duration of the 50-Hz stimulation, was noted in almost every nerve root or posterior rootlet that was stimulated, and this response was usually associated with ipsilateral lower-limb spread outside of the immediate segmental distribution of the nerve root being stimulated. Thus, according to the criteria that had been described, almost every rootlet could be considered abnormal (that is, involved in the maintenance of spasticity). In our unit, the decision to cut certain posterior nerve rootlets was based not on the finding that some rootlets were "normal" whereas others were "abnormal," but on the findings that some rootlets were more abnormal than others.

Change in Electrophysiological Criteria

To determine what the so-called "normal" response might be in humans, dorsal nerve root stimulation was performed in five children who had no spasticity in the limbs. These children were not truly "normal" because they were having operations for a tethered spinal cord, but they had no spasticity or upper motor neuron findings. In these patients, it was noted that sustained responses to 50-Hz stimulation at the threshold level were common, so that such responses did not necessarily identify a nerve root or rootlet that might be involved in the spastic process. In these nonspastic children 50-Hz stimulation produced minimal, if any, spread to the muscles of the contralateral lower limb or to the muscles of the upper limb, neck, and face.[17,18]

Based on the above findings, the electrophysiological criteria used during SFPR were changed for Phase 3 patients. The threshold of the response and the occurrence of a sustained response to 50-Hz stimulation were ignored, and the only criterion that was utilized was the extent of spread of the response contralaterally and suprasegmentally.

We were not unique in recognizing that there were problems with the original electrophysiological criteria of Fasano, *et al.*,[8] and Peacock and Arens.[14] Others have also modified the electrophysiological criteria used in SFPR, although along different lines. Vaughan, *et al.*,[21] examined in detail the pattern of the so-called "sustained" response noted during 50-Hz stimulation and considered decremental patterns to be normal and incremental patterns to be abnormal. Storrs and Nishida[20] utilized a different approach during rhizotomy for the identification of rootlets involved in the spastic process. They assessed the H-reflex recovery curve in response to intraoperative bipolar stimulation of posterior nerve rootlets and used an H2/H1 ratio of more than 50% as their criterion for abnormality, sectioning rootlets with ratios above this level. No attempt was made to validate these newer electrophysiological criteria by comparison of the findings in nonspastic children with those in spastic patients.

Effect of Changing the Electrophysiological Criteria

The current study was designed to analyze the effects of changing the electrophysiological criteria, with respect to both the extent of division of each posterior nerve root and patient outcome. In patients undergoing SFPR using the new electrophysiological criteria (Phase 3), the total amount of posterior nerve root division was less than in the earlier patients. The simple interpretation of this finding is that the new electrophysiological criteria are more valid indicators of nerve roots involved in the spastic process and therefore allow a more precise definition of the nerve rootlets that are to be divided, resulting in the ability to spare more of the noninvolved rootlets. This would certainly fit nicely with the underlying concept of SFPR. There is a confounding issue, however, in that at approximately the time the electrophysiological criteria were changed, there was a trend in many centers toward cutting fewer posterior nerve roots than had been cut previously. Because we were aware of this trend from personal discussions, it is possible that the decrease in the percentage of nerve roots cut might have been in part related to a change in our philosophy about how much of each nerve root to cut and not totally to the change in electrophysiological criteria.

If the concept underlying SFPR is correct and if the new electrophysiological criteria used in Phase 3 are more valid and precise than the original criteria, then in theory one should be able to achieve at least as good a reduction in spasticity and as good an outcome with transection of a smaller percentage of the posterior nerve roots using the new criteria compared to the original criteria. The results of this study indicate that in all phases of the study there was a significant decrease in spasticity and an increase in range of movement following rhizotomy. The degree of reduction in spasticity was least in Phase 3, when the new electrophysiological criteria were used, but the improvement in range of lower-limb movement was similar in all three phases of the study. More important than the change in spasticity and range of motion are the functional changes that occur in patients after SFPR. No difference was observed in functional outcome in the three phases of the study, with respect to changes in locomotion, improvements in lower-limb function, and suprasegmental effects.

One interpretation of the results is that the new electrophysiological criteria do allow a more precise definition of the posterior nerve rootlets involved in the spastic process, and therefore permit both good reduction of spasticity and functional improvement with transection of fewer nerve rootlets. This is an attractive conclusion and fits with the concept of SFPR. Another explanation may be that it simply is not necessary to cut as much of each posterior nerve root as was being cut initially to reduce spasticity adequately and that it is not necessary to relieve spasticity completely to achieve a good functional result.

There is no consistency in the literature regarding the appropriate percentage of the posterior nerve root to cut. Fasano and coworkers[9,10] commented that in 23% of their cases they cut fewer than 25% of the posterior nerve rootlets, in 75% of cases they cut 25% to 50%, and only in 2.5% of cases did they cut more than 50% of the rootlets. On the other hand, Barolat,[4] who developed the procedure of SFPR with Fasano and colleagues, noted that in his experience "the vast majority of the reflex responses are abnormal" and "in most cases, depending on the severity of the clinical involvement, the percentage of stimulated rootlets that are actually sectioned varies between 60% and 90%."[4] When the goal of the procedure was ambulation, less than 70% of the rootlets were sectioned, and in severely incapacitated patients up to 95% of the rootlets were cut.[4] Peacock and coworkers[14,15] in their early reports did not indicate what percentage of the posterior nerve roots was cut when they used the original criteria of Fasano, *et al.*,[8] but using their modified electrophysiological criteria between 25% and 50% of the posterior nerve rootlets were sectioned in a group of patients in whom ambulation was the goal.[21] Storrs and Nishida[20] cut an average of 67% of posterior nerve rootlets; Newberg, *et al.*,[12] 64%; Park, *et al.*,[13] between 50% and 80% at each level; and Abbott, *et al.*,[2] between 40% and 70% at each level. Irrespective of the percentage of posterior nerve rootlets cut and the electrophysiological criteria used, all centers have reported good outcomes.

An unresolved issue is whether using intraoperative electrical stimulation as the basis for selection of posterior nerve rootlets to be cut, whatever electrophysiological criteria are used, results in better relief of spasticity and better functional outcome than performing predetermined partial posterior rhizotomies. One might expect that if the electrophysiological criteria were unrelated to the effectiveness of the operation in reducing spasticity, the decrease in spasticity across the three phases of this study would be associated with the percentage of posterior nerve roots transected, irrespective of what electrophysiological criteria were used. There was significantly less reduction in spasticity after SFPR in Phase 3, when the new electrophysiological criteria were used, than in Phase 1, when the original criteria were used and a larger percentage of the posterior nerve roots were cut, suggesting a correlation between the amount of nerve root transection and the relief of spasticity. However, when a detailed analysis of the relationship between the percentage of posterior nerve roots divided and the extent of the decrease in spasticity was performed for all patients in the study, no correlation was identified.

Conclusions

Concurrent with and perhaps because of the change in electrophysiological criteria used to determine which posterior nerve rootlets to cut during SFPR, the percentage of posterior nerve roots being transected decreased. Despite cutting less, spasticity was reduced significantly, although less than previously, and the increase in range of lower-limb movement and functional improvement were not different from those attained previously. Further studies are needed to determine if functional selection of nerve rootlets for rhizotomy on the basis of patient responses to intraoperative electrical stimulation is any better than performing predetermined partial posterior rhizotomies.

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