



Clinically practical formula for preoperatively estimating the cutting rate of the spinal nerve root in a functional posterior rhizotomy

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Abstract

Objective A functional posterior rhizotomy (FPR) ideally involves minimal cutting of the posterior root while providing maximal reduction of disabling spasticity. However, the ideal cutting rate has yet to be determined. It was hypothesized that the cutting rate of the posterior root would negatively correlate with preoperative motor function in children with spasticity.

Methods Children who underwent an FPR between March 1996 and March 2017 and whose pre- and postoperative data were followed more than a year were enrolled. The preoperative Gross Motor Function Measure (GMFM) score and the overall cutting rate of the posterior root were plotted on a scatter plot, and a simple linear regression analysis was performed. The rationale for the cutting rate of the posterior root was tested by postoperative chronological changes in the GMFM score up to 5 years after the FPR. The Gross Motor Function Classification System (GMFCS) was used to group the children. The postoperative and preoperative GMFM were compared at each GMFCS level.

Results One hundred thirty-seven children (aged 2 to 19 years old, mean 5.9 years old) met the selection criteria. The cutting rate of the posterior root ranged from 17 to 83%, (mean 48.3%). A scatter plot was then made using GMFM scores between 10 and 90. The formula for the simple linear regression analysis was $y = -0.5539x + 73.896$ (x , GMFM score; y , overall cutting rate (%)). The formula was further approximated based on the scatter plot findings as $y = 100 - x$. The postoperative GMFM showed an improved average score for all GMFCS levels although statistically significant improvement at postoperative 5 years was confirmed in only the GMFCS level 1 group.

Conclusions The findings of this study supported the hypothesis of the negative correlation of the cutting rate of the posterior root with preoperative motor function in children with spasticity. The amount of posterior nerve root/rootlet cutting during FPR negatively correlated with the preoperative GMFM score. The approximated formula is simple, practical for clinical use, and helpful for preoperatively estimating the required overall cutting rate for the posterior root. The suggested cutting rate induced by the approximated formula should be used as a reference value and be modified according to preoperative motor function, severity and distribution of spasticity, the result of intraoperative neurophysiology, and other factors.

Keywords Rhizotomy · Spasticity · GMFM · Surgery · Cerebral palsy

Introduction

The functional posterior rhizotomy (FPR) aims to reduce spasticity and is indicated mainly for children with spasticity due to cerebral palsy but is also effective for the treatment of

spasticity due to other conditions [2, 34, 42, 43]. In the latter part of the nineteenth century, FPR was performed to relieve intractable neurogenic pain [1]. Foerster, a German neurologist and neurosurgeon, first employed the procedure to treat spasticity more than a century ago using electrical stimulation of the nerve root for intraoperative neurophysiological monitoring [47]. In his paper of 1913, he cautioned against cutting the L4 posterior root because of its importance for ambulation [12]. The surgery, once known as “Foerster’s operation,” was revived in the 1970s when Fasano introduced modern intraoperative neurophysiological procedures to select the posterior root/rootlet for cutting [10]. Peacock later modified this surgical technique by moving the surgical field from the conus to the cauda equina [34]. Shifting the surgical field enabled the

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precise level of the spinal nerve root to be located, and this procedure became standard practice in FPR. Park performed the operation at the level of the conus with a single level laminectomy, which later became another major surgical technique in FPR [32]. Currently, FPR is one of the standard treatments for managing spasticity thanks to the pioneering work of these neurosurgeons.

The usefulness of FPR for reducing spasticity is widely acknowledged [3, 4, 9, 18, 23, 24, 26, 42, 43, 45, 48]. However, the criteria for selecting the nerves and the extent of cutting remain controversial. A variety of neurophysiological criteria for identifying abnormal nerve roots / rootlets exist, but their reliability and usefulness are disputed [7, 11, 13, 14, 17, 30, 35, 40, 44]. Moreover, there are no guidelines on how much cutting is appropriate for reducing disabling spasticity while preserving sufficient tonus for the motor and truncal support functions (beneficial spasticity).

The author herein hypothesized that the extent to which the posterior nerve root/rootlet was cut would correlate with pre-operative motor function, i.e., that children with severe spasticity and limited motor function would require more cutting while those with only mild spasticity and relatively intact motor function would require less. The hypothesis had already been suggested in the meta-analysis of three randomized controlled trials which mentioned “the initial functional level may have influenced the extent of transection” [24]. This study proved the hypothesis using the Gross Motor Function Measure (GMFM) score to assess motor function and provided a simple, practical, clinical formula for estimating the cutting rate of the posterior nerve root/rootlet [37].

Methods

FPR was performed by the author in 198 children between March 1996 and March 2017. The candidates for FPR were children with spastic para- or tetraparesis originating in the brain. The majority of the children suffered from cerebral palsy but those suffering from other brain pathologies such as encephalitis, ischemic encephalopathy, degenerative brain disease, and brain damage of unknown origin were also included. From these children, those preoperatively classified using the Gross Motor Function Classification System (GMFCS) and those pre- and postoperatively evaluated using GMFM for more than 1 year were selected for this study (Table 1). GMFM-88 was used to evaluate motor function since spastic children with a condition other than cerebral palsy and those with severe spasticity (GMFCS levels 4 and 5) were included in this cohort [19, 22, 37, 39, 49]. Pre- and postoperative chronological changes in the GMFM score were used to verify that the rate of nerve root/rootlet cutting during surgery was appropriate. Previously published data and the motor development curve of children with cerebral palsy were used as references [9, 18, 26, 36, 48]. This

Table 1 Demographic data of the children with spasticity

Characteristics	Value
No. of children	137
Age	
Range (years)	2–19
Mean \pm SD (years)	5.9 \pm 3.0
Median (years)	5
Sex	
Boy	92
Girl	45
Pathology	
Cerebral palsy	128
Other	9
Surgery	
Standard	97
Limited	39
Conus medullares	1
Cutting rate	
Range (%)	17–83
Mean \pm SD (%)	48.3 \pm 18.1
Median (%)	51

study was approved by the institutional review board of the Tokyo Metropolitan Children’s Medical Center.

Surgery

Peacock’s standard procedure was the surgical procedure of choice for FPR [32]. In addition, modified Peacock’s procedure (limited procedure) and surgery at the conus medullaris were used [15, 33]. The modified version of Peacock’s procedure excluding the involvement of the L2 and L3 roots was first introduced in February 1999. Since then, the modified procedure has been performed for selected children with mild to moderate spasticity (GMFCS levels 1 to 3) predominantly localized in the ankle joint [15]. Details of the surgical procedures have been described elsewhere [27, 29].

Intraoperative neurophysiology was carried out in all cases. Pudendal mapping was performed to preserve urogenital function [8]. The L2-S2 range of the posterior root was tested for FPR. However, the S2 posterior root usually contains the highest amplitude of the pudendal afferent action potential and is usually not susceptible to lesioning [31].

The selection of the posterior root/rootlet for cutting was guided by intraoperative neurophysiology. Some other factors and clinical findings such as age, the distribution and degree of spasticity, the presence of mental retardation, and preoperative locomotive function were also taken into consideration before making the final decision of whether or not to cut the root.

The neurophysiological criteria for abnormality were based on the extent of segmental muscle contraction and the absence of restriction of muscle contractions on repetitive stimulation (10 Hz) [2, 10, 13, 27, 30]. The intraoperative neurophysiological response was the most important factor in determining whether or not to cut the root/rootlet. However, in order to avoid postoperative functional deterioration, the following criteria were also applied during an FPR [27, 29]:

- 1) No more than three successive roots should be totally (100%) cut [2].
- 2) Total cutting of the S1 posterior root should be avoided if the patient had any ambulatory function.
- 3) The maximum overall cutting rate should be less than 85%.
- 4) The minimum overall cutting rate should be more than 15%.

The overall cutting rate for the posterior root was calculated by averaging the cutting rate of both sides of the L2-S1 posterior root. When the modified procedure was used, the cutting rate for L2 and L3 was counted as zero and averaged (Fig. 1).

Statistical analysis

The relationship between the cutting rate and the preoperative GMFM score was examined by plotting the results on a scatter plot. The correlation coefficient was determined, and a simple linear regression analysis was carried out using Microsoft

Excel Statistical Function (Microsoft, Excel for Mac, version 15.32).

Functional improvement after the FPR as seen in the preoperative GMFM and the postoperative GMFM at 5 years was analyzed statistically for each GMFMS Level. The Student's *t* test was used to detect statistical differences with StatCalc version 8.2.2 (AcaStat Software, USA). *P* < 0.05 was considered statistically significant.

Results

In total, 137 children (92 boys and 45 girls, age 2 to 19 years, mean age 5.9 years, median age 5 years) were enrolled. FPR was carried out using the standard procedure in 97 children, the modified procedure in 39 children, and at the conus medullaris in one child. The cutting rate for the posterior root/rootlet ranged from 17 to 83% (mean 48.3%, median 51%). The background characteristics of the children are shown in Table 1.

The preoperative GMFM-88 score was recorded for all children, but follow-up data at 1 month, 1 year, 2 years, 3 years, 4 years, and 5 years were available in 110, 133, 95, 71, 33, and 37 children, respectively. The number of children classified in GMFCS levels 1 to 5 was 12, 17, 39, 42, and 27, respectively.

At GMFCS level 1, the cutting rate for the posterior root/rootlet ranged from 17 to 30% (the mean ± SD was 21.3 ± 3.3%). The average GMFM was 91.3 preoperatively and 94.3 and 98.0 at postoperative years 1 and 5, respectively.

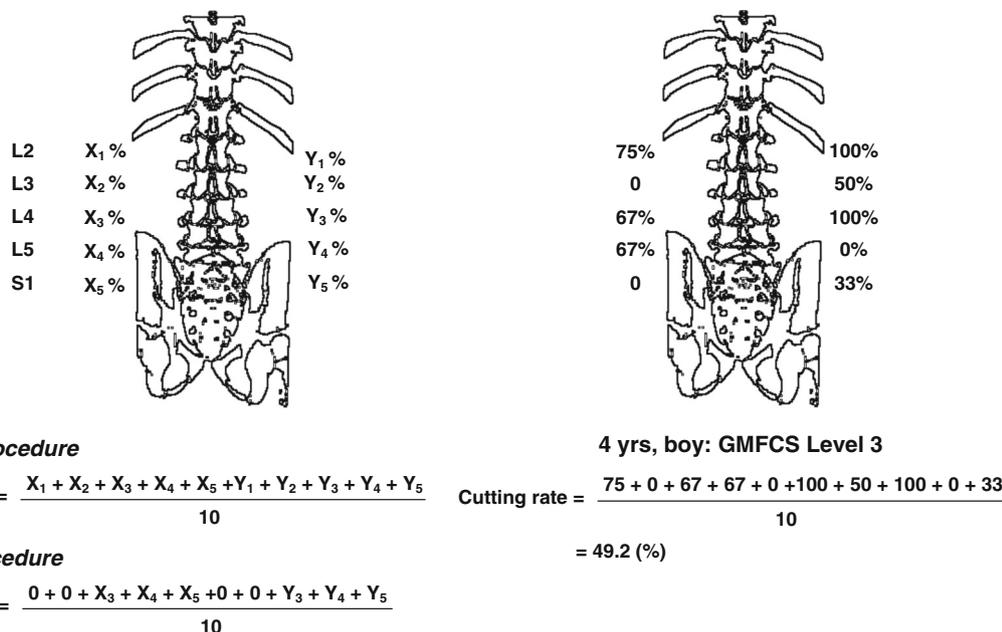


Fig. 1 Calculation of overall cutting rate. Left: Overall cutting rate for the posterior root was calculated by averaging the cutting rates for the L2-S1 posterior roots on both sides. When the limited (modified) procedure was

used, the cutting rate for L2 and L3 was counted as zero and averaged. Right: Example of calculation of the overall cutting rate. The cutting rates for all the posterior roots from L2-S1 on both sides were averaged

At GMFCS level 2, the cutting rate ranged from 19 to 38% (the mean ± SD was 26.4 ± 4.7%). The average GMFM score was 76.4 preoperatively and 82.4 and 90.8 at postoperative years 1 and 5, respectively. In GMFCS level 3, the cutting rate ranged from 21 to 59% (the mean ± SD was 41.1 ± 9.7%). The average GMFM was 59.5 preoperatively and 64.7 and 72.4 at postoperative years 1 and 5, respectively. In GMFCS level 4, the cutting rate ranged from 34 to 77% (the mean ± SD was 58.6 ± 7.4%). The average GMFM was 33.3 preoperatively and 36.1 and 41.4 at postoperative years 1 and 5, respectively. In GMFCS level 5, the cutting rate ranged from 49 to 83% (the mean ± SD was 70.0 ± 8.3%). The average GMFM was 6.0 preoperatively and 7.3 and 6.8 at postoperative years 1 and 5, respectively. Table 2 shows the details of the chronological changes in the GMFM scores. The mean GMFM score at postoperative year 5 marked an improvement from the preoperative GMFM score at all GMFCS levels, but statistically significant improvement was confirmed only for the GMFCS level 1 group.

The relationship between the overall cutting rate of the posterior root/rootlet and GMFM score is displayed on a scatter plot (Fig. 2). The correlation coefficient in Fig. 2 was -0.89, suggesting a very high negative correlation between the cutting rate and GMFM score. The formula for the simple linear regression analysis of all the data was:

$$y = -0.5539x + 73.896 \text{ (dotted line in Figure 2)}$$

x (independent variable): GMFM score

y (dependent variable): cutting rate

In order to remove the influence of the limitations on the maximum and minimum cutting rates, only GMFM scores between 10 and 90 were plotted in Fig. 3. The maximum overall cutting rate even in a child with a GMFM score below 10 was kept below 85% regardless of intraoperative neurophysiological

abnormalities. Conversely, in a child with a GMFM score above 90, the minimum cutting rate was applied and the overall cutting rate rose above 15%. The correlation coefficient in Fig. 3 was -0.82, suggesting a very high negative correlation between the GMFM score and the cutting rate. The formula for the simple linear regression analysis in this cohort was:

$$y = -0.5765x + 75.514 \text{ (dotted line in Figure 3)}$$

Discussion

Cutting rate for the posterior root/rootlet

Whether or not root/rootlet cutting is sufficient to reduce disabling spasticity while preserving muscle tone (beneficial spasticity) in the trunk and extremities is a major concern for pediatric neurosurgeons performing FPR. Postoperative hypotonia should be avoided to improve motor function, especially in children who are ambulatory [15, 41]. With rootlet cutting of 50–75%, Kim et al. reported long-standing postoperative hypotonia in 3.5% among their 208 cases [20]. On the other hand, fewer posterior root/rootlet cutting can result with lower improvement of GMFM after FPR [24].

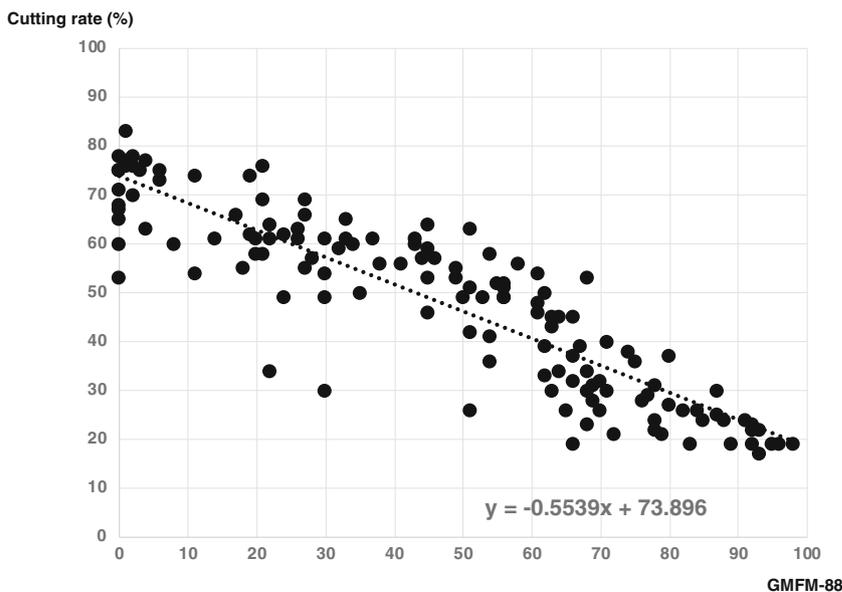
Maximum reduction of spasticity with minimum cutting of the posterior root/rootlet is ideal [15]. A report from the Vancouver group described chronological reduction of the cutting rate from more than 70% to 25–70% [21]. It may be assumed that children with severe spasticity require more cutting while those with mild spasticity require less [24, 28]. However, to the best of the author’s knowledge, no data have been published on the cutting of the root/rootlet in relation to preoperative motor function in spastic children.

In his pioneering, historic paper, Foerster described total (100%) posterior root cutting from L2 to S1 while sparing the L4 root [12]. After the World War II, Foerster’s procedure

Table 2 Chronological changes in GMFM-88 score at each GMFCS level

GMFCS Level		Preop. GMFM	Postop. GMFM						GMFM p value
			1 month	1 year	2 years	3 years	4 years	5 years	
1	mean ± SD± n = 12	91.3 ± 3.0 12	81.7 ± 12.1 12	94.3 ± 3.5 12	95.3 ± 2.6 9	94.5 ± 3.9 5	97.5 ± 1.1 4	98.0 ± 0.7 4	p < 0.0183
2	mean ± SD n = 17	76.4 ± 7.7 17	73.1 ± 13.7 9	82.4 ± 8.4 17	83.5 ± 10.0 8	88.8 ± 7.5 9	88.2 ± 3.2 6	90.8 ± 8.0 8	p < 0.4161
3	mean ± SD n = 39	59.5 ± 12.9 39	57.0 ± 12.5 35	64.7 ± 13.1 38	64.9 ± 14.6 32	69.2 ± 15.2 21	77.6 ± 13.3 12	91.3 ± 3.0 9	p < 0.2197
4	mean ± SD n = 42	33.3 ± 14.6 42	30.0 ± 14.1 31	36.1 ± 15.8 41	35.9 ± 15.8 30	36.8 ± 14.1 25	44.1 ± 5.5 9	41.4 ± 9.5 8	p < 0.1161
5	mean ± SD n = 27	6.0 ± 8.5 27	5.0 ± 8.8 23	7.3 ± 11.3 23	7.6 ± 10.9 16	7.7 ± 11.0 11	(-) 0	6.8 ± 8.6 6	p < 0.4244

Fig. 2 Relationship between overall cutting rate of posterior root/rootlet and GMFM-88 score (all data). The scatter plot shows the distribution of all data. The formula for the simple linear regression analysis of all the data is $y = -0.5539x + 73.896$ (x , GMFM-88 score; y , overall cutting rate) and is shown by the dotted line



was modified by Gros et al. by sectioning 80% of each posterior root from L2 to S1 in order to reduce the sensory complications and postoperative hypotonia [16]. In his review, Steinbok described cutting each of the L2–S1 posterior roots from 20 to 70%, with an overall cutting rate between 50 and 70% [45]. Abel reported 60 to 70% posterior rootlet cutting from L3 to S1 and less cutting at L1 and L2 [3]. Park et al. normally cut 60 to 70% of the posterior rootlets from L1 to S2 or 60 to 70% from L2 to S1 and 50% of L1 [30]. It should be noted that these data were included in a

supplementary section on surgical procedures, and no paper has dealt primarily with the cutting rate for the posterior root/rootlet.

Formula for estimating the cutting rate preoperatively

The author proposed a formula for estimating the posterior root/rootlet cutting rate preoperatively. Given the maximum

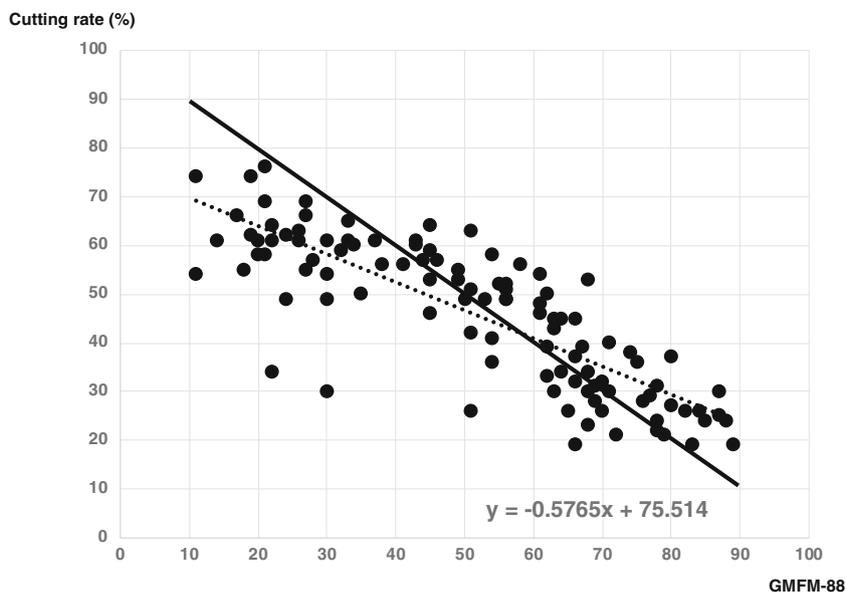


Fig. 3 Relationship between the overall cutting rate of the posterior root/rootlet and GMFM-88 scores ranging from 10 to 90. The scatter plot shows the distribution of the overall cutting rate when the GMFM score is restricted to the range 10–90. The formula for the simple linear regression analysis of all the data is $y = -0.5765x + 75.514$ (x , GMFM-88

score; y , overall cutting rate) and is shown by the dotted line. The approximated formula $y = 100 - x$ is shown by the straight line. The simple approximated formula also matches the distribution of the plotted data and is recommended for daily clinical use to estimate the overall cutting rate in FPR preoperatively

and minimum cutting rule described before, the following formula shown in Fig. 3 is more appropriate for clinical use:

$$y = 75.514 - 0.5765x$$

Appropriateness of the formula may be verified by the postoperative chronological improvement in GMFM scores. Children who underwent FPR showed better outcomes than who did not [36]. The results of FPR in this study are in line with previously published data on FPR based on long-term follow up using GMFM [4, 9, 18, 26, 48]. The findings also corroborate the author's hypothesis that the rate of posterior root/rootlet cutting negatively correlates with preoperative motor function.

The formula is based on a statistical method using simple linear regression analysis. When looking at the distribution of the plotted data in Fig. 3, a simpler approximation of the formula:

$$y = 100 - x$$

where y is the estimated cutting rate (%) and x is the preoperative GMFM score (shown as a straight line in Fig. 3), also provides a preoperative estimate of the overall cutting rate. The formula is not correct from a statistical perspective but is nevertheless suited for clinical use because of its simplicity. The author recommends this simple formula as an alternative approximation. In practice, the estimated cutting rate serves as a guide and should be modified based on preoperative information, intraoperative findings, and the result of intraoperative neurophysiology. It should also be borne in mind that the given overall "estimated cutting rate" is not absolute but relative and that it should be used as a reference value by the surgeon intraoperatively. For example, if the GMFM of a child is 45, the estimated cutting rate calculated by the alternative simple formula is 55% ($100 - 45 = 55$). The result should suggest to the surgeon that an overall cutting rate of about 50 to 60% would be sufficient for the patient to achieve a reduction in spasticity while avoiding hypotonia due to over-cutting of the root [2].

Role of intraoperative neurophysiology in FPR

Knowledge of intraoperative neurophysiology is important during an FPR for two reasons: first, it helps to preserve the urinary function by localizing the pudendal afferent pathway and second, it allows identification of the abnormal segmental reflex circuit in the spinal cord. Pudendal mapping was used for the first purpose and electrical stimulation of the posterior root/rootlet was carried out for the latter purpose [8, 10, 13, 25, 30, 35].

FPR has enjoyed a resurgence in popularity over the past several decades thanks to the Italian neurosurgeon, Fasano, who introduced the neurophysiological procedure to judge which posterior root/rootlet needed cutting to reduce spasticity [10]. This theoretical decision-making procedure, based on the neurophysiological response, has attracted much attention,

and a variety of criteria have been published [2, 11, 14, 25, 29, 33, 34]. However, skeptics contend that the neurophysiological response under general anesthesia is not always repeatable and that the borderline between abnormal and "normal" responses is sometimes ambiguous [7, 40, 44, 46].

In the author's practice, intraoperative neurophysiology plays a major role when selecting the posterior root/rootlet for cutting. Neurophysiologically-guided, function-based decision-making is the basic concept of this study. However, at the same time, other factors such as preoperative motor function and the severity and distribution of disabling spasticity are also considered to be important determinants. Thus, the results of posterior root/rootlet cutting described here are closer to those of a "selective" than "non-selective" rhizotomy.

The GMFM-88 versus GMFM-66

The GMFM is a tool for assessing gross motor function in children with spasticity. The GMFM-88 "is a criterion-referenced observational measure specifically developed to evaluate changes in gross motor function over time in children across the wide spectrum of ability levels in cerebral palsy" [19, 38]. The scoring system targets children with spasticity and has been validated for use with patients with Down syndrome and other disabilities as well [38]. On the other hand, the GMFM-66 is used strictly for children with cerebral palsy. Its 66 items, selected by Rasch analysis from the original GMFM-88 (88 items), are considered to be the most important means of assessing gross motor function in children with cerebral palsy [6, 19].

The utility and reliability of both GMFM scoring systems have been established [5, 21]. In general, the GMFM-88 is recommended for use with severely disabled children such as those at GMFCS levels 4 or 5 [19, 38]. The GMFM-88 was chosen for this study cohort since spasticity caused by cerebral palsy and other pathologies were included, and nearly half of the children were ranked at GMFCS levels 4 or 5.

Limitations of the study

The study has several limitations. The results were derived from the experience of the author's surgical practice alone. The author's estimates of the cutting rate at the time of surgery may not always have been accurate [13]. The author always tried to divide a root evenly into several rootlets. Although any given cutting rate for a nerve root is always an approximation, an attempt was made to adjust the cutting rate visually if the division was uneven.

Another limitation was that the maximum and minimum cutting rates were pre-determined. A limit on the maximum cutting rate was necessary to avoid postoperative sensory complications and hypotonia. The minimum cutting rate requirement was necessary to achieve a reduction of spasticity in children with GMFCS levels 1 and 2.

Finally, preoperative motor function was an important consideration when deciding how much of a root/rootlet should be cut whenever the limited procedure was applied. In children with mild to moderate motor deterioration (GMFCS level 1 to 3), L2 and L3 were excluded. Thus, the intraoperative neurophysiological examination was not the single major determinant of the extent of cutting and the level of the spinal root at which the cutting should be done in children with FPR using the limited procedure.

Conclusion

The findings of this study corroborated the author's hypothesis that the amount of posterior nerve root/rootlet cutting during FPR correlates with preoperative motor function.

The approximated simple formula was:

$$y = 100 - x$$

which would be useful in daily clinical practice.

Despite the limitations of study, the modified formula should help pediatric neurosurgeons performing an FPR to determine how much of posterior root/rootlet rhizotomy is sufficient to reduce disabling spasticity while preserving beneficial spasticity. A future prospective study using the modified formula is needed to test its effectiveness in reducing spasticity after FPR.

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Compliance with ethical standards

Conflict of interest The author has no conflict of interest.

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