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Three-column osteotomy versus Halo-gravity traction combined with posterior column osteotomy in the treatment of dystrophic neurofibromatosis type 1 kyphoscoliosis: a retrospective comparative cohort study

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Abstract

Background Dystrophic neurofibromatosis type I (NF1) kyphoscoliosis presents unique challenges for corrective spinal surgery due to anatomical abnormalities. To compare the radiographic and clinical outcomes of dystrophic neurofibromatosis type 1 (NF1) kyphoscoliosis patients undergoing three-column osteotomy (3CO), halo-gravity traction (HGT), or posterior column osteotomy (PCO) and to evaluate their efficacy and safety in this cohort, different treatment strategies and their associated complication rates warrant further comprehensive investigation.

Methods Dystrophic NF1 kyphoscoliosis were divided into 3CO, HGT, and PCO groups based on the surgical strategy. Radiographic parameters were measured preoperatively, postoperatively, and at each follow-up. Intraoperative and postoperative complications were recorded for each patient, and patient-reported outcomes were assessed using the Scoliosis Research Society-22 (SRS-22) questionnaire. Differences among the three groups were analyzed.

Results A total of 9 patients were included in the 3CO, 22 in HGT group, 95 in PCO groups, respectively. Significant differences among the three groups were found in terms of operation time ($p = 0.011$), estimated blood loss ($p = 0.003$), and number of satellite rod techniques ($p = 0.013$). At pre-operation, the Cobb angles of main curves were 84.3 ± 24.6° in 3CO group, 99.1 ± 24.3° in HGT group, 60.0 ± 16.8° in PCO group. At post-operation, significant post-operative improvements were found in the Cobb angles of the main curves, apical vertebral translation (AVT), segmental kyphosis (SK), and deformity angular ratio (DAR) in all three groups ($p < 0.001$). No significant correction

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loss was observed during the follow-up. Six complications were found in the 3CO group, 13 in the HGT group, and 40 in the PCO group.

Conclusions PCO, 3CO, and HGT could be applied to dystrophic NF1 patients. The 3CO is also associated with increased perioperative complications.

Level of evidence IV.

Keywords Three-column osteotomy, Halo-gravity traction, Posterior column osteotomy, Neurofibromatosis type 1, Kyphoscoliosis

Introduction

Neurofibromatosis type 1 (NF1) has been identified as a significant cause of severe spinal kyphoscoliosis, posing a substantial challenge for spine surgeons [1, 2]. Anatomically, dystrophic NF1 scoliosis is frequently associated with vertebral rotatory subluxation, dysplastic pedicles, and vertebral scalloping [3, 4], which collectively contribute to a markedly higher risk of intraoperative and postoperative complications. Despite these challenges, it is important to emphasize that surgery remains the only effective treatment strategy for patients with severe dystrophic NF1 kyphoscoliosis [5].

Posterior column osteotomy (PCO) is routinely performed to achieve extensive spinal release and a high correction rate. In recent years, three-column osteotomies (3CO), including pedicle subtraction osteotomy (PSO) [6], SRS-Schwab Grade 4 osteotomy [7], and vertebral column resection (VCR) [8], have been widely utilized for severe and rigid scoliosis caused by various etiologies. Additionally, preoperative halo-gravity traction (HGT) is strongly recommended for patients with severe and rigid deformities or those at a high risk of iatrogenic neurological complications [9–11]. Despite the relatively extended duration of preoperative treatment, HGT significantly enhances clinical and radiographic outcomes by increasing curve flexibility, reducing neurological risks associated with gradual traction on a chronically tethered cord, and improving pulmonary function [11–13].

Although PCO and HGT have been extensively studied in patients with dystrophic NF1, the literature on the application of 3CO in this population remains scarce, with its clinical and radiographic outcomes being a subject of debate. Therefore, this retrospective study was designed with the following objectives: (1) to compare the radiographic and clinical outcomes of dystrophic NF1 patients undergoing 3CO, HGT, or PCO and (2) to evaluate the efficacy and safety of 3CO and HGT in this cohort.

Materials and methods

Subjects

We retrospectively reviewed patients with dystrophic NF1 who underwent surgical treatment between January 2010 and December 2020. The inclusion criteria were as follows: (1) diagnosis of NF1 based on the criteria established by the Consensus Development Conference on Neurofibromatosis [14]; (2) presence of three or more dystrophic features identified on spinal radiography, CT, or MRI; (3) apex of the main curve located in the thoracic or lumbar spine; (4) undergoing posterior spinal correction surgery; (5) a minimum of 2 years of postoperative follow-up; and (6) complete radiographic data available for preoperative, postoperative, and follow-up evaluations.

Exclusion criteria included: (1) history of prior spinal surgery and (2) undergoing anterior release, halo-femoral traction, or halo-pelvic traction. The patients were subsequently divided into three groups:

1. 3CO group: patients who underwent three-column osteotomy at the apex or apex + 1.
2. HGT group: patients who received preoperative halo-gravity traction followed by one-stage posterior spinal correction surgery without 3CO.
3. PCO group: patients who underwent posterior-only spinal correction surgery with multilevel posterior column osteotomy.

Ethical approval for this study was obtained from the Clinical Research Ethics Committee of our hospital.

Three column osteotomy (3CO) procedure

The 3CO procedures utilized in this study included Schwab grade 4 PSO [7] and grade 5 VCR [8]. The indications for 3CO were as follows: (1) patients with severe and rigid deformities with deformity angular ratio (DAR) > 30 (°/level); (2) those unable or unwilling to undergo HGT; (3) patients with mature and adequate pulmonary function test results, and a prognostic nutritional index (PNI) ≥ 45; (4) presence of type 1 or type 2 spinal cord morphology with cerebrospinal fluid (CSF) visible at the curve apex [15, 16]; and (5) absence of symptomatic neurological deficits preoperatively. It is important to emphasize that 3CO is recommended with caution and is performed only after careful consideration.

Halo-gravity traction (HGT) procedure

The indications for HGT were as follows: (1) severe and rigid spinal deformities with deformity angular ratio (DAR) > 30 (°/level) and (2) progressive neurological deficits or compromised cardiopulmonary function or a prognostic nutritional index (PNI) < 45. An individualized halo ring with four to six pins was applied under local anesthesia. The initial traction weight was set at 3–4 *kg* and gradually increased by 2 *kg* per day. The target weight ranged from 30 to 50% of the patient's body weight based on individual tolerance and did not exceed 15 *kg*. Traction was maintained for more than 12 h daily, with the weight reduced by half during nighttime hours.

Posterior column osteotomy (PCO) procedure

The PCO procedure was performed in all the patients across the three groups. PCO is typically performed in the apex region and the lumbar spine. The resected elements included the inferior and superior articular facets, ligamentum flavum, lamina, and spinous process. The procedure adhered to the SRS-Schwab Grade 2 osteotomy classification [17].

Radiographic parameters

The following radiographic parameters were measured preoperatively, postoperatively, and at each follow-up: (1) Cobb angle of the main curve; (2) coronal imbalance; (3) apical vertebral translation (AVT); (4) segmental kyphosis (SK); (5) deformity angular ratio (DAR); (6) thoracic kyphosis (TK); (7) lumbar lordosis (LL); (8) sagittal vertical axis (SVA); (9) pelvic incidence (PI); (10) pelvic tilt (PT); and (11) sacral slope (SS).

Clinical assessment

The intra-operative and post-operative complications were recorded for each patient. Patient-reported outcomes were assessed using the Scoliosis Research Society-22 (SRS-22) questionnaire. Data from the questionnaires, independently completed by the patients preoperatively and at each follow-up, were analyzed.

Statistical analysis

SPSS software (version 19.0; SPSS, Inc.) was used for statistical analysis. Descriptive statistics were performed to analyze the patients' demographics. Normality assessment for all continuous variables was conducted using the Shapiro-Wilk test (for sample sizes below 50) or the Kolmogorov-Smirnov test (for sample sizes ≥ 50), with distribution characteristics determining analytical approaches. Data demonstrating normal distribution were expressed as mean ± standard deviation (SD), whereas variables with non-normal distributions were reported as median (Q1, Q3). To ensure uniformity in data presentation, all continuous variables at a given time point are summarized as median (Q1, Q3) if any variable within that time point exhibits a non-normal distribution. Specific variables exhibiting non-normal distributions across cohorts included: (1) age, (2) postoperative TK, (3) the last follow-up CB and (4) the last follow-up SVA. Categorical data were compared using the chi-squared or Fisher's exact test. For normally distributed continuous variables: paired t-tests assessed longitudinal changes between preoperative and postoperative measurements, while intergroup comparisons utilized independent-sample t-tests (for two groups) or one-way ANOVA (for three groups). Non-normally distributed variables underwent Wilcoxon signed-rank tests for paired longitudinal analyses and Kruskal-Wallis H tests with Dunn's post hoc correction for multiple-group comparisons. Statistical significance was set at *p*-value < 0.05.

Results

Demographics

Nine patients (5 males and 4 females) were included in the 3CO group, 22 (13 males and 9 females) in the HGT group, and 95 (51 males and 44 females) in the PCO group. Comparison analysis showed significant differences among the three groups in terms of operation time ($p = 0.011$), estimated blood loss ($p = 0.003$), and number of satellite rod techniques ($p = 0.013$). The general data are shown in Table 1.

Radiographic outcomes

At pre-operation, the Cobb angles of main curves were 84.3 ± 24.6° in 3CO group, 99.1 ± 24.3° in HGT group, 60.0 ± 16.8° in PCO group, and significant difference were observed among 3 groups ($p < 0.001$). Statistical differences among the three groups were also revealed in terms of coronal imbalance, AVT, SS, TK, SK, and DAR ($p < 0.05$). The details of the radiographic parameters preoperatively are shown in Table 1.

For patients in HGT group, the average post-traction values were 77.1 ± 25.5° for Cobb angle of main curve, 21.8 ± 14.9 *mm* for coronal imbalance, 51.8 ± 27.4 *mm* for AVT, 1.9 ± 9.6° for PT, 37.2 ± 12.7° for PI, 35.3 ± 11.9° for SS, 58.4 ± 23.6° for LL, 45.4 ± 27.9° for TK, 27.8 ± 16.5 *mm* for SVA, 78.5 ± 29.6° for SK, and 37.2 ± 11.3°/level for DAR. Significant differences were observed in the Cobb angle of the main curve ($p < 0.001$), AVT ($p = 0.047$), SVA ($p = 0.013$), SK ($p < 0.001$), and DAR ($p < 0.001$).

At post-operation, The Cobb angles of main curves decreased to 41.7 ± 14.7° in 3CO group, 51.7 ± 22.7° in HGT group, 32.2 ± 15.7° in PCO group, and significant improvement was reported ($p < 0.001$ for all 3 groups). Similarly, significant post-operative improvements were found in AVT, SK, and DAR in all three groups ($p < 0.001$). Postoperative radiographic parameters are shown in Table 2, and radiographic parameters at the last

Table 1 The demographic and radiographic data at pre-operation in 3 groups

Group(*N*)	3CO group (9)	HGT group (22)	PCO group (95)	*p*-value
Gender (M/F)	5/4	13/9	51/44	0.899
Age (y) $	17(13, 29.5)	14(12.8, 17.3)	14(12, 15)	0.135#
Apex (T/L)	7/2	18/4	70/25	0.588
Fusion levels (vertebra)	13.0±1.8	12.0±2.0	11.6±2.2	0.135
Operation time (*min*)	367.8±92.0	316.8±107.1	283.7±80.7	**0.011**
Estimated Blood loss (*ml*)	1878.9±483.6	1138.0±400.5	970.3±349.2	**0.003**
No. of satellite rod technique	6(66.7%)	10(45.5%)	24(25.3%)	**0.013**
Follow-up (m)	39.1±10.4	37.6±12.2	43.6±16.1	0.204
Cobb angle of main curve (°)	84.3±24.6	99.1±24.3	60.0±16.8	**<0.001**
Coronal imbalance (*mm*)	37.2±20.0	25.9±17.7	15.9±13.8	**<0.001**
AVT (*mm*)	54.8±25.6	56.8±24.8	42.4±16.0	**0.002**
PT (°)	12.2±10.3	3.6±11.3	9.6±24.2	0.445
PI (°)	36.1±7.7	36.4±14.2	43.8±25.0	0.284
SS (°)	23.8±9.6	32.9±12.4	34.2±9.6	**0.016**
LL (°)	59.4±31.5	59.5±22.0	50.3±18.1	0.090
TK (°)	61.7±45.5	51.3±29.5	26.4±17.5	**<0.001**
SVA (*mm*)	32.4±16.7	39.8±19.2	30.3±20.2	0.133
SK (°)	80.0±24.8	88.5±27.8	36.2±17.6	**<0.001**
DAR (°/level)	40.8±8.8	44.6±11.7	23.2±7.1	**<0.001**

*Abbreviations: AVT: apical vertebral translation; SK: segmental kyphosis; DAR: deformity angular ratio; TK: thoracic kyphosis; LL: lumbar lordosis; SVA: sagittal vertical axis; PI: pelvic incidence; PT pelvic tilt; SS: sacral slope

** The value was listed as mean ± standard deviation. ***Boldface values indicate statistically significant

$ The data in the table are represented as median (Q1, Q3)

The Kruskal-Wallis test was chosen

follow-up are shown in Table 3. Compared with the post-operative parameters, no significant loss of correction was observed at the last follow-up despite the presence of coronal imbalance in both the HGT and PCO groups.

Clinical outcomes

At the last follow-up, the SRS-22 measures showed significant improvements in self-image and mental health in all three groups when compared with the pre-operative values ($p < 0.05$). The average scores of satisfaction were 4.22 ± 0.51 for 3CO group, 4.27 ± 0.46 for HGT group, and 4.29 ± 0.43 for PCO group. The detailed data are listed in Table 4.

Complications

Six complications were found in the 3CO group, 13 in the HGT group, and 40 in the PCO group. In the 3-CO group, incidental dural tears occurred in 2 cases (22.2%). In comparison, 1 case each was observed in the HGT (4.5%) and PCO (1.1%) groups. Regarding intraoperative neurological monitoring alerts, such events were noted in 2 cases (22.2%) in the 3-CO group, 3 cases (13.6%) in the HGT group, and 4 cases (4.2%) in the PCO group. A new permanent neurological deficit was reported in one patient in the 3CO group and a new transient neurological deficit in one patient in the PCO group with fully recovery in postoperative 6 months. Apart from incidental dural tears and intraoperative neurological monitoring alerts, which demonstrated statistically significant differences among the three groups ($p = 0.011$ and $p = 0.037$, respectively), other mechanical complications—including pedicle screw misplacement (0 vs. 2 vs. 5 cases), proximal or distal junctional kyphosis (0 vs. 2 vs. 16 cases), coronal or sagittal decompensation (1 vs. 3 vs.6 cases), and implant failure (0 vs. 2 vs. 7 cases)—did not show any statistically significant differences between groups ($p > 0.05$). Revision surgery was performed in 1 patient in the HGT group and in 2 patients in the PCO group. The detailed data are listed in Table 5.

Discussions

It is well established that the natural history of dystrophic scoliosis in patients with neurofibromatosis type 1 (NF1) is marked by a high propensity for rapid curve progression, during which both the primary and compensatory curves can become rigid and structural. The primary objective of surgical intervention for dystrophic scoliosis associated with neurofibromatosis type 1 (NF1) is to achieve a physiologically balanced spinal alignment accompanied by a robust and solid internal fusion. However, the distinctive anatomical abnormalities associated with neurofibromatosis type 1 (NF1) present considerable challenges for pedicle screw placement, often resulting in reduced implant density and necessitating a limitation in the application of corrective forces. Consequently, soft-tissue release and various osteotomy techniques have

Table 2 The radiographic data at post-operation in 3 groups

	3CO group	**HGT group**	**PCO group**	***p*-value (between groups)**
Cobb angle of main curve (°)	41.7±14.7	51.7±22.7	32.2±15.7	**<0.001**
p-value (pre- vs. post-op)	**<0.001**	**<0.001**	**<0.001**	
Coronal imbalance (*mm*)	12.8±7.1	24.6±15.2	18.3±13.9	0.063
p-value (pre- vs. post-op)	**0.005**	0.744	0.225	
AVT (*mm*)	35.3±22.5	37.0±21.3	23.0±14.0	**<0.001**
p-value (pre- vs. post-op)	**0.002**	**<0.001**	**<0.001**	
PT (°)	10.8±11.5	0.32±8.6	13.6±31.0	0.126
p-value (pre- vs. post-op)	0.399	0.126	0.248	
PI (°)	37.2±7.6	33.9±8.1	46.4±29.9	0.108
p-value (pre- vs. post-op)	0.278	0.214	0.448	
SS (°)	26.4±9.6	33.6±9.5	32.7±8.9	0.110
p-value (pre- vs. post-op)	0.254	0.759	0.112	
LL (°)	48.4±12.1	48.4±14.4	43.6±12.3	0.191
p-value (pre- vs. post-op)	0.216	**0.007**	**<0.001**	
TK (°) $	26.1(17.0, 50.5)	28.8(10.5, 33.3)	17.8(13.1, 22.6)	**0.003**#
p-value (pre- vs. post-op)	**0.021**	**<0.001**##	0.886	
SVA (mm)	28.4±34.6	29.7±23.4	29.2±31.0	0.994
p-value (pre- vs. post-op)	0.776	0.145	0.758	
SK (°)	25.4±19.6	35.1±25.3	27.5±10.9	0.081
p-value (pre- vs. post-op)	**<0.001**	**<0.001**	**<0.001**	
DAR (°/level)	16.6±6.2	21.9±10.1	14.5±6.0	**<0.001**
p-value (pre- vs. post-op)	**<0.001**	**<0.001**	**<0.001**	

*Abbreviations: AVT: apical vertebral translation; SK: segmental kyphosis; DAR: deformity angular ratio; TK: thoracic kyphosis; LL: lumbar lordosis; SVA: sagittal vertical axis; PI: pelvic incidence; PT pelvic tilt; SS: sacral slope

** The value was listed as mean ± standard deviation. ***Boldface values indicate statistically significant

$ The data in the table are represented as median (Q1, Q3)

The Kruskal-Wallis test was chosen

The Mann-Whitney U test was chosen

become essential components of surgical management in this patient population. In clinical practice, posterior column osteotomy (PCO) is regarded as a fundamental technique for the correction of dystrophic scoliosis associated with neurofibromatosis type 1 (NF1) [18, 19]. Over the past few decades, preoperative halo-gravity traction (HGT) has been increasingly employed to enhance the safety and efficacy of spinal deformity correction, particularly in cases involving severe or rigid curves, vertebral rotatory subluxation, and neurological deficits [10, 20, 21]. For patients who are unable or unwilling to undergo halo-gravity traction (HGT), three-column osteotomy (3CO) remains the sole viable option for attaining satisfactory radiographic and clinical outcomes [18, 19]. This study was designed to comprehensively evaluate the utilization and clinical outcomes of three distinct treatment strategies in patients with dystrophic scoliosis associated with neurofibromatosis type 1 (NF1).

Preoperative radiographic parameters were compared among the three treatment groups in this study. The preoperative Cobb angles of the main curves were 84.3 ± 24.6° in the 3CO group, 99.1 ± 24.3° in the HGT group, and 60.0 ± 16.8° in the PCO group, revealing a statistically significant difference among the groups, as expected. Similarly, measures of coronal imbalance, apical vertebral translation (AVT), sacral slope (SS), thoracic kyphosis (TK), segmental kyphosis (SK), and deformity angular ratio (DAR) were notably higher in the 3CO and HGT groups compared to the PCO group. These findings collectively suggest that 3CO and HGT are primarily employed in patients presenting with more severe and rigid spinal deformities.

The effectiveness of halo-gravity traction (HGT) in improving spinal deformities has been well documented in previous studies [10, 22–24], with reported correction rates varying according to the underlying etiology, curve flexibility, deformity severity, and duration of traction. Koller et al. [24] reported mean correction rates of 15.1% for scoliosis and 16.5% for kyphosis in cases involving rigid and severe scoliosis and kyphoscoliosis. Similarly, Han et al. [25] demonstrated average correction rates of 35.98% in the coronal plane and 33.27% in the sagittal plane following HGT. In a cohort of 35 patients with severe neurofibromatosis type 1 (NF1) and congenital scoliosis (CS) treated with HGT, Shi et al. [10] reported mean correction rates of 22.5% for the coronal

Table 3 The radiographic data at the last follow-up in 3 groups

	3CO group	HGT group	PCO group	*p*-value (between groups)
Cobb angle of main curve (°)	42.8±18.7	52.9±22.5	32.7±14.6	**<0.001**
p-value (post-op vs. FU)	0.744	0.658	0.739	
Coronal imbalance (*mm*) $	25.0(11.2, 43.0)	8.8(5.9, 18.3)	11.6(5.2, 18.8)	0.051#
p-value (post-op vs. FU)	0.436	**0.003**##	**0.023**##	
AVT (*mm*)	32.9±22.0	39.2±19.1	21.2±11.7	**<0.001**
p-value (post-op vs. FU)	0.366	0.534	0.096	
PT (°)	7.8±10.6	2.2±9.0	9.7±18.3	0.169
p-value (post-op vs. FU)	0.219	0.339	0.182	
PI (°)	36.8±8.3	36.2±11.1	44.2±18.1	0.079
p-value (post-op vs. FU)	0.642	0.304	0.456	
SS (°)	29.0±5.9	34.0±11.5	34.5±8.0	0.185
p-value (post-op vs. FU)	0.283	0.885	0.064	
LL (°)	49.5±16.6	50.3±18.3	44.7±12.1	0.162
p-value (post-op vs. FU)	0.806	0.613	0.475	
TK (°)	31.2±16.2	29.8±20.0	25.4±10.2	0.193
p-value (post-op vs. FU)	0.948	0.250	0.382	
SVA (*mm*) $	24.9(9.2, 31.4)	21.1(4.9, 37.4)	20.9(11.9, 39.6)	0.732#
p-value (post-op vs. FU)	0.387	0.367	0.526##	
SK (°)	25.2±20.3	36.4±24.0	30.6±16.4	0.195
p-value (post-op vs. FU)	0.892	0.131	0.180	
DAR (°/level)	16.7±7.6	23.2±10.2	15.1±6.1	**<0.001**
p-value (post-op vs. FU)	0.965	0.099	0.266	

*Abbreviations: AVT: apical vertebral translation; SK: segmental kyphosis; DAR: deformity angular ratio; TK: thoracic kyphosis; LL: lumbar lordosis; SVA: sagittal vertical axis; PI: pelvic incidence; PT pelvic tilt; SS: sacral slope

** The value was listed as mean ± standard deviation. ***Boldface values indicate statistically significant

$ The data in the table are represented as median (Q1, Q3)

The Kruskal-Wallis test was chosen

The Mann-Whitney U test was chosen

Table 4 Comparison of SRS-22 measures between pre-operation and the last follow-up

		3CO group	HGT group	PCO group	*p*-value (between groups)
Pre-op	Pain	3.71±0.46	3.77±0.42	3.80±0.50	0.839
	Self-image	3.02±0.53	2.95±0.43	3.10±0.42	0.347
	Mental Health	3.23±0.40	3.21±0.46	3.30±0.45	0.676
	Satisfaction	-	-	-	
	Function	3.58±0.43	3.50±0.49	3.57±0.42	0.781
Last follow-up	Pain	3.64±0.24	3.88±0.42	3.86±0.40	0.276
	p (pre-op vs. FU)	0.631	0.296	0.216	
	Self-image	4.07±0.49	4.03±0.43	4.13±0.43	0.593
	p (pre-op vs. FU)	**<0.001**	**<0.001**	**<0.001**	
	Mental Health	4.13±0.48	4.05±0.44	4.06±0.45	0.891
	p (pre-op vs. FU)	**<0.001**	**<0.001**	**<0.001**	
	Satisfaction	4.22±0.51	4.27±0.46	4.29±0.43	0.883
	p (pre-op vs. FU)	-	-	-	
	Function	3.67±0.35	3.65±0.40	3.61±0.34	0.867
	p (pre-op vs. FU)	0.616	0.277	0.217	

*The value was listed as mean ± standard deviation. **Boldface values indicate statistically significant

Cobb angle and 24.6% for sagittal kyphosis. In the present study, significant improvements were observed in the Cobb angle of the main curve, apical vertebral translation (AVT), sagittal vertical axis (SVA), segmental kyphosis (SK), and deformity angular ratio (DAR) following traction. These findings underscore the utility of halo-gravity traction (HGT) in patients with severe dystrophic spinal deformities, with higher correction rates often associated

Table 5 The summary of intra-op and post-op complications in 3 groups

	3CO group (*N*=9) (%)	HGT group (*N*=22) (%)	PCO group (*N*=95) (%)	*p*-value
Misplacement of pedicle screws	0	2(9.1)	5(5.3)	0.772
Incidental dural tear	2(22.2)	1(4.5)	1(1.1)	**0.011**
Neurologic monitoring alert	2(22.2)	3(13.6)	4(4.2)	**0.037**
New neurological deficit	1(11.1)	0	1(1.1)	0.166
Proximal/distal junctional kyphosis	0	2(9.1)	16(16.8)	0.438
Coronal/sagittal decompensation	1(11.1)	3(13.6)	6(6.3)	0.408
Implant failure	0	2(9.1)	7(7.4)	0.835
Revision	0	1(4.5)	2(2.1)	0.571

*Boldface values indicate statistically significant

with enhanced postoperative spinal realignment. Previous studies have also demonstrated the effectiveness of HGT in improving vertebral rotatory subluxation and pulmonary function [10, 22]. Postoperative radiographic outcomes represent a primary concern for both spine surgeons and patients. Cai et al. [18] examined the surgical management and prognosis of 27 patients with neurofibromatosis type 1 (NF1) presenting with severe dystrophic kyphosis, reporting satisfactory radiographic outcomes following both low-grade (grades 1–2) and high-grade (grades 3–6) osteotomies, thereby demonstrating the efficacy of both surgical approaches in this patient population. Similarly, Shi et al. [10] reported overall postoperative correction rates of 31.2% for the coronal Cobb angle and 44.6% for global kyphosis in patients who underwent halo-gravity traction (HGT) as part of their treatment protocol.

In the present study, significant postoperative improvements were observed in the Cobb angle of the main curve, apical vertebral translation (AVT), segmental kyphosis (SK), and deformity angular ratio (DAR) across all three groups, further supporting the efficacy of the respective surgical techniques. Importantly, no significant loss of correction was noted during follow-up, and coronal imbalance showed significant improvement in both the HGT and PCO groups. Cai et al. [18] similarly reported shorter operative times, reduced intraoperative blood loss, and shorter hospital stays in the low-grade osteotomy group compared to the high-grade group. These findings suggest that higher-grade osteotomies are associated with increased procedural complexity, greater surgical trauma, and prolonged postoperative recovery.

Clinical outcomes represent another critical concern for patients undergoing spinal deformity correction. Existing evidence indicates that satisfactory clinical results can be achieved through posterior spinal correction surgery, three-column osteotomy (3CO) [25], or halo-gravity traction (HGT) [26]. Shi et al. [25] reported statistically significant improvements in self-image scores among patients with severe kyphoscoliosis who underwent Society-Schwab Grade 6 osteotomy. Similarly, Grabala et al. [27] demonstrated significant improvements across all domains of the Scoliosis Research Society-22 (SRS-22) questionnaire in patients treated with preoperative HGT. In the present study, SRS-22 scores revealed significant postoperative improvements in self-image and mental health across all three groups at the final follow-up compared with preoperative values, further corroborating the findings of these prior investigations [25–27].

Previous studies have emphasized that one-stage posterior spinal correction and fusion in patients with severe deformities present considerable challenges and are associated with a high incidence of intraoperative complications. In the Scoli-RISK-1 study, which evaluated complication rates in complex spinal deformity surgeries, Kelly et al. [28] reported an overall complication rate of 49.3%, including a 8.7% incidence of new neurological deficits. Similarly, Papadopoulos et al. [29] analyzed the clinical and radiographic outcomes of 45 patients who underwent posterior three-column osteotomy and reported a total of 29 intraoperative and postoperative complications. In the present study, 6 complications were observed in the 3CO group, 13 in the HGT group, and 40 in the PCO group. Regarding incidental dural tears, all cases were managed intraoperatively with primary suturing of the dural defect to ensure no cerebrospinal fluid (CSF) leakage, followed by reinforcement with a hemostatic tissue sealant. Regarding intraoperative neurological monitoring alerts, all alerts occurred during the osteotomy procedures. The surgical team responded with a standardized protocol that included: (1) increasing intraoperative mean arterial pressure (MAP) to >80 mmHg, (2) transfusion to maintain hemoglobin levels above 10 g/dL, (3) administration of intravenous corticosteroids to mitigate procedure-related neural edema, and (4) expediting the completion and closure of the osteotomy. Following these measures, the surgical field was irrigated with sterile warm saline to enhance local circulation. Neurological recovery was confirmed through improvement in intraoperative signals, followed by a wake-up test to double-check the restoration of distal lower limb motor function.

Notably, iatrogenic neurological deficits were identified in two patients—one permanent case in the 3CO group and one transient case in the PCO group. Furthermore, the incidence of incidental dural tears and intraoperative neuromonitoring alerts was significantly higher in the 3CO group compared to the other groups ($p = 0.011$ and $p = 0.037$, respectively). The elevated rate of neurological complications in the 3CO group may be attributed to the highly invasive nature of the three-column osteotomy technique, which involves extensive bone resection, as well as the presence of anatomical abnormalities such as dural ectasia commonly associated with dystrophic neurofibromatosis type 1 (NF1). Moreover, due to the inherent complexity and invasiveness of the 3-CO procedure, prolonged operative time and increased blood loss are almost unavoidable. This is supported by our study data, which showed significantly longer operative time ($p = 0.011$) and greater blood loss ($p = 0.003$) in the 3-CO group. These two factors may have further contributed to the increased surgical difficulty and higher complication rate observed in this group. These complications can cause irreversible damage and poor clinical outcomes.

The findings of this study indicate that even in cases of severe dystrophic NF-1 kyphoscoliosis, a surgical approach combining HGT with PCO may be a viable alternative to 3CO. This strategy achieves comparable clinical and radiographic outcomes while significantly reducing the risk of neurological complications.

Illustrated cases

A 13-year-old girl diagnosed with dystrophic NF-1 kyphoscoliosis underwent spinal correction surgery consisting of T10/11 VCR and posterior spinal fusion (PSF). The Preoperative measurements included a main Cobb angle of 140°, SK of 130°, and DAR of 47° per level. Postoperatively, the main Cobb angle was reduced to 70°, SK to 50°, and DAR to 26° per level. The procedure is complicated by an incidental dural tear. At the 2-year follow-up, no significant loss of correction in radiographic parameters was observed. This case is illustrated in Fig. 1.

A 17-year-old boy diagnosed with dystrophic NF-1 kyphoscoliosis underwent an 8-week course of HGT, followed by spinal correction surgery consisting of PCO and PSF. Preoperative measurements included a main Cobb angle of 133°, SK of 105°, and DAR of 44° per level. Postoperative measurements showed a reduction in the main Cobb angle to 90°, SK to 35°, and DAR to 28° per level. At the 2-year follow-up, no significant loss of correction was observed and no complications were reported. This case is illustrated in Fig. 2.

Limitations

The primary limitation of this study was the relatively small sample size, particularly in the subgroup of NF1 patients who underwent three-column osteotomy (3CO).

Fig. 1 A 13-year-old female with dystrophic NF-1 kyphoscoliosis underwent T10/11 VCR + PSF, reducing Cobb angle from 140° to 70°, SK from 130° to 50°, DAR from 47° to 26° per level. Despite an incidental dural tear, no correction loss was observed at the 2-year follow-up

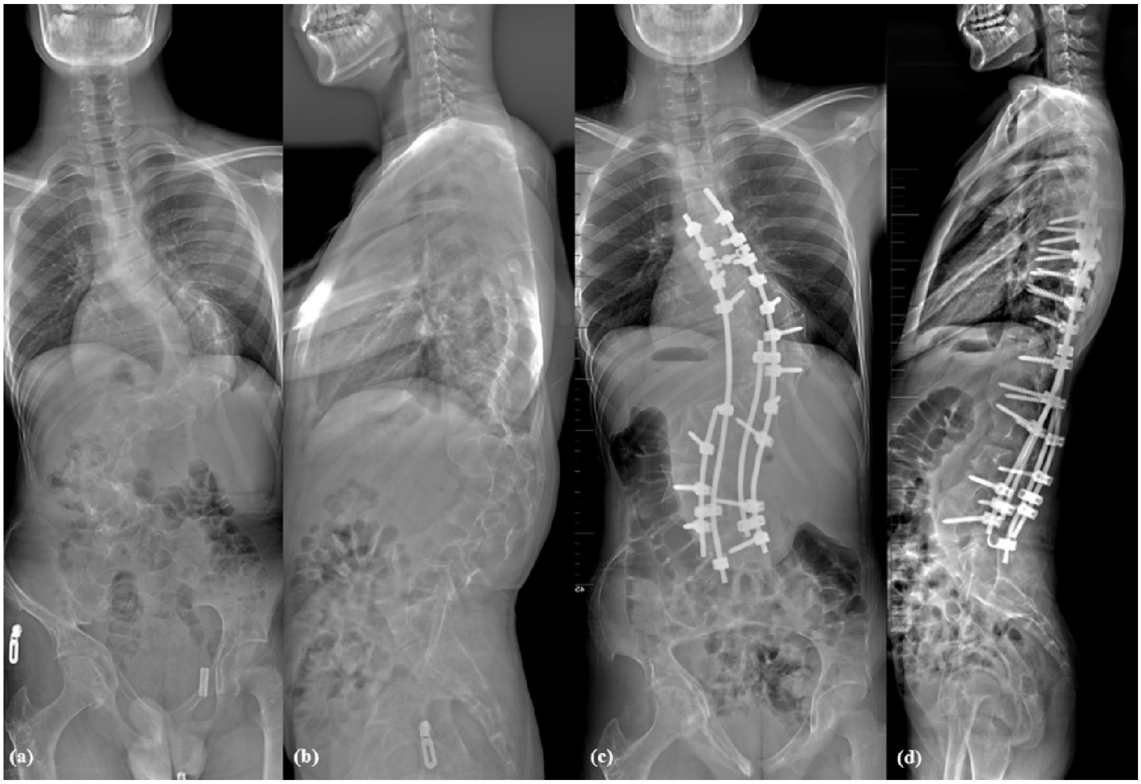

Fig. 2 A 17-year-old male with dystrophic NF-1 kyphoscoliosis underwent HGT followed by PCO + PSF, reducing Cobb angle from 133° to 90°, SK from 105° to 35°, DAR from 44° to 28° per level. At the 2-year follow-up, no correction loss or complications were observed

Due to this constraint, more robust statistical analyses, such as logistic regression, could not be reliably conducted. Furthermore, given the presence of dystrophic changes in this patient population, the 2-year postoperative follow-up period may be insufficient to comprehensively evaluate implant-related complications. Variability in curve patterns and fusion strategies among the three groups may also have introduced bias into the study's conclusions. Therefore, a multicenter investigation with a larger sample size and extended longitudinal follow-up is warranted to enable a more comprehensive evaluation of the outcomes and risks associated with 3CO in patients with severe dystrophic neurofibromatosis type 1 (NF1).

Conclusions

Posterior column osteotomy (PCO), three-column osteotomy (3CO), and halo-gravity traction (HGT) are all effective surgical strategies for the management of dystrophic scoliosis in patients with neurofibromatosis type 1 (NF1), each demonstrating satisfactory radiographic and clinical outcomes. However, the 3CO technique is associated with longer operative duration, increased estimated blood loss, and a higher risk of perioperative complications. For patients with severe dystrophic neurofibromatosis type 1 (NF1) scoliosis, we recommend a treatment strategy involving preoperative halo-gravity traction (HGT), followed by a one-stage posterior column osteotomy (PCO), deformity correction, and posterior spinal fusion (PSF).

Abbreviations

NF-1	dystrophic neurofibromatosis type I
3CO	three-column osteotomy
HGT	halo-gravity traction
PCO	posterior column osteotomy
VCR	vertebral column resection
PSO	pedicle subtraction osteotomy
SRS-22	Scoliosis Research Society-22 questionnaire
AVT	apical vertebral translation
SK	segmental kyphosis
DAR	deformity angular ratio
TK	thoracic kyphosis
LL	lumbar lordosis
SVA	sagittal vertical axis
PI	pelvic incidence
PT	pelvic tilt
SS	sacral slope

Supplementary Information

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Supplementary Material 1

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Author contributions

YS Lo and YT Dai contributed equally to this study and share first authorship. All authors contributed to the manuscript and approved the submitted version. We declare that AI-assisted technologies were not used to generate scientific or interpreted data. AI technologies were only used to perform grammar checks on the completed manuscripts to improve linguistic accuracy under the supervision of all authors.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent for publication

For underage participants, informed consent was obtained through legal guardians, who signed on their behalf and ensured that the participants were adequately informed and fully understood the nature of the study. Written consent was obtained from all study participants, and approval was obtained from the Institutional Review Board of China Medical University Hospital (CMUH114-REC1-34256).

Competing interests

The authors declare no competing interests.

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