



EVALUATION OF THE OUTCOMES OF NEUROSURGICAL AND ORTHOPEDIC INTERVENTIONS IN SPINAL DYSRAPHISM SYNDROME FROM THE PERSPECTIVE OF THE DYNAMICS OF OBJECTIVE DIAGNOSTIC CRITERIA FOR SPINAL CORD TETHERING AND TRACTION SYNDROME

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Objective. To evaluate the diagnostic value of clinical and instrumental criteria for tethered cord syndrome (TCS) by analyzing the outcomes of the main types of neurosurgical and orthopedic interventions.

Material and Methods. The retrospective continuous 3-center study included 120 patients operated for TCS in spinal dysraphism. Based on functional outcome assessment, patients were divided into three groups: patients in Group 1 underwent microsurgical redetethering, in Group 2 — shortening three-column vertebrotomy (Schwab 3–6) with correction of spinal deformity and instrumental fixation; and in Group 3 (control) — without reoperation. Groups were assessed for the nosological structure of dysraphism based on the neurosegmental level of damage according to Sharrard, frequency of surgical interventions, dynamics of motor status and spasticity according to the Ashworth scale, sensory impairment, urinary control and bladder tone according to urodynamic studies, MR signs of spinal cord tethering syndrome, types of musculoskeletal deformities, as well as treatment outcomes according to uniform assessment criteria.

Results. Statistically significant differences in the frequency of unfavorable outcomes depending on the type of surgery were shown. Redetethering was associated with an increased risk of unfavorable outcome (61%; $p = 0.044$), shortening vertebrotomy showed significant predominance of favorable outcome ($p = 0.036$): 7% unfavorable versus 27% favorable. Analysis of the initial diagnosis did not reveal significant differences between the study groups in terms of the types of dysraphism and neurosegmental level of damage, nosological structure, motor status assessment, the number of interventions performed to eliminate spinal cord tethering, as well as the frequency of spinal deformities. At the same time, the analysis of lower extremity pathology revealed statistically significant differences in patients with kyphosis ($p < 0.01$), leg deformities ($p = 0.019$), and hip dislocation ($p = 0.001$).

Conclusion. Redetethering in spinal dysraphism syndrome is associated with an increased risk of adverse outcomes; shortening vertebrotomy demonstrates the best results. Key prognostic factors for adverse outcomes are significant orthopedic deformities, including foot deformities and hip dislocations, which reflect the severity of damage to neural structures and serve as clinical markers for risk stratification. It is advisable to personalize unification of conventional approaches to treating tethered cord syndrome in spinal dysraphism; the interdisciplinary nature of the problem requires the development of standardized algorithms for managing these patients.

Key Words: spinal dysraphism; retethering; detethering; vertebrotomy.

Please cite this paper as: Ryabykh SO, Kalashnikov AA, Klimov VS, Gorchakov SA. Evaluation of the outcomes of neurosurgical and orthopedic interventions in spinal dysraphism syndrome from the perspective of the dynamics of objective diagnostic criteria for spinal cord tethering and traction syndrome. Russian Journal of Spine Surgery (Khirurgiya Pozvonochnika). 2026;23(2):6–15. In Russian. DOI: <http://dx.doi.org/10.14531/ss2026.2.6-15>

Tethered spinal cord syndrome (TSCS) is a severe complication of spinal dysraphism, pathogenetically linked to the fixation of the spinal cord, which leads to cord ischemia and progressive neurological, urological, and orthopedic deficits [1].

Although the diagnosis and surgical treatment of spinal dysraphism have advanced significantly, timely identification and longitudinal monitoring of TSCS continue to pose a major challenge in pediatric neurosurgery and orthopedics. Existing diagnostic frameworks for

TSCS frequently rely on isolated clinical features and neuroimaging findings, without fully integrating their complex, dynamic interactions [2, 3]. Assessing the outcomes of combined treatment, encompassing neurosurgical intervention (modes of spinal cord untethering)

and corrective orthopedic spinal surgery, remains specifically challenging.

This underscores the clinical significance and necessity of developing and validating standardized, sensitive, and specific clinical diagnostic criteria for TSCS in spinal dysraphism, as well as reliable methods for monitoring their dynamics following various neurosurgical and orthopedic interventions.

The study objective is the evaluation of the diagnostic value of clinical and instrumental criteria for tethered and tensioned spinal cord syndromes based on outcome analysis of major neurosurgical and orthopedic interventions. A previous systematic literature review [4] established the primary diagnostic criteria for tethered spinal cord syndrome (TSCS) in spinal dysraphism: low-lying conus medullaris, shortened fatty filum terminale, and lumbosacral lipoma. Consequently, the diagnostic criteria for TSCS include hydrocephalus, conus medullaris dystopia below the L1–L2 level, syringomyelia, lipoma of the filum terminale, thickening of the filum terminale to 2 mm or greater, caudal regression syndrome, and cerebellar tonsillar ectopia.

However, criteria for an integrated assessment of patients' clinico-mor-

phofunctional status are currently lacking, and existing scales are non-specific. Although the described MRI criteria are limited by their level of evidence, they reflect a high level of expert consensus, including the determination of indications for surgical untethering of the spinal cord [5–7]. The absence of clear indications for surgical intervention and the debate surrounding prophylactic hardware removal necessitate further study of the issue, with an emphasis on analyzing TSCS criteria [8, 9].

To achieve the stated objective, we set out to address three specific tasks: (1) to conduct a comparative analysis of the clinical and neuroimaging manifestations of TSCS across various forms of spinal dysraphism; (2) to evaluate the dynamics of clinical and neuroimaging manifestations following neurosurgical and orthopedic correction at different postoperative follow-up intervals; (3) to assess the outcomes of neurosurgical and orthopedic correction based on the analysis of objective diagnostic parameter trends.

Material and Methods

Study design. A retrospective, comprehensive, three-center study conduct-

ed in accordance with the principles of the Declaration of Helsinki and the PICO framework (Table 1). Level of evidence – 2c according to the 2009 UK Oxford CEBM Levels of Evidence ('outcomes research').

Study population. The study enrolled 120 patients with TSCS secondary to spinal dysraphism who underwent surgery performed by three surgical teams across three specialized institutions: Research Clinical Institute of Pediatrics and Pediatric Surgery n.a. Yu.E. Veltischev (Moscow), St. Vladimir Children's City Clinical Hospital (Moscow), and Pirogov Clinic of High Medical Technologies of the Saint Petersburg State University. The control group consisted of patients of identical age and disease entity who were managed by the same specialist teams but did not undergo microsurgical redetethering and shortening vertebroto-

Data enrollment period: January 2022 to June 2025

Based on the functional outcome assessment, the patients were divided into three groups: Group 1 underwent microsurgical redetethering; Group 2 underwent shortening three-column osteotomy; and Group 3 (control) no resurgery.

Table 1
PICO framework

PICO elements	Inclusion criteria	Exclusion criteria
Members	Pediatric patients (<18 years) who underwent or did not undergo primary or staged surgical treatment for tethered cord syndrome	Adult patients (<18 years) with non-dysraphic tethered cord syndrome. Data deficit during the screening and treatment phases
Intervention	Microsurgical detethering of the spinal cord (Microsurgical spinal cord redetethering). Three-column shortening osteotomy (Schwab 3–G) for spinal deformity correction and instrumental fixation (shortening vertebroto-). Control group (non-reoperated)	Removal of spinal canal tumors without detethering of the spinal cord and its elements. Posterior spinal osteotomy (Schwab 1–2) with deformity correction and instrumented fixation
Comparison	Analysis of the nosological structure by neurosegmental level of lesion according to Sharrard. Outcome evaluation: Group 0 – favorable outcome; Group 1 – adverse outcome	—
Results	Baseline and changes in neurological and orthopedic status (see evaluation criteria). Clinical data (complications). Brain and spinal cord MRI data (see assessment criteria)	—

Table 2

Study parameters and cohort evaluation criteria

Parameters	Assessment criteria
Motor status and sensory impairment	Lower extremity paresis/paralysis according to Frankel. Level of sensory impairment Spasticity assessment under Ashworth
Urodynamic deficit	Assessment of bladder control (urinary incontinence/retention) Changes in bladder compliance according to multichannel urodynamic study findings
Musculoskeletal deformities	Hip dislocation / bilateral hip dislocation. Sagittal spinal deformity magnitude. Progression of foot deformities (equino-cavo-varus, plano-varus, calcaneus, and equino-valgus foot deformities and their variants). Progression of large joint contractures of the lower extremities
Brain and spinal cord MRI	Low-lying conus medullaris. Evidence of syringomyelia. Evidence of myelopathy. Lipoma of the filum terminale and thickening of the filum terminale to 2 mm or greater. Verification of new lipomas and dermal sinuses

The study parameters and assessment criteria are detailed in Table 2.

General characteristics of the study group. The study included 120 patients with TSCS secondary to spinal dysraphism. Functional outcomes were evaluated across three groups based on the treatment strategy: Group 1, microsurgical redetethering; Group 2, shortening vertebratomy; and Group 3, control (no reoperation).

Assessment criteria. The following parameters were evaluated:

- the nosological structure of spinal dysraphism, including classification by the neurosegmental level of lesion according to Sharrard [10, 11].
- number of surgeries;
- dynamics of spasticity on the Modified Ashworth Scale (MAS)
- sensory impairment and motor function of the limbs using the Frankel Scale;
- Urinary continence capability and detrusor tone according to urodynamic data;
- MRI findings suggestive of TSCS;
- variants of musculoskeletal deformities; the types of foot deformities are detailed in Table 2; the axial skeletal deformities were analyzed in the sagittal plane, assuming a direct impact on TSCS; the severity of kyphosis was graded according to the Winter classification

(grade 1: 30–40° Cobb angle; grade 2: 40–50°; grade 3: >50° and <70°; grade 4: >70°), along with the presence of hyperlordosis (>60° Cobb angle).

Treatment outcome assessment criteria

Adverse outcome criteria:

1) lack of improvement and/or progression of neurological deficit (persistent or worsening limb paresis/paralysis, increasing spasticity or emergence of new pathological reflexes, lack of pain regression).

2) advancement of pelvic organ dysfunction (worsening of urinary control [urinary incontinence/retention], recurrent urinary tract infections, and deterioration of neurogenic bladder based on urodynamic data);

3) advancement of secondary orthopedic conditions (progression of spinal deformity, foot deformities, and contractures of major joints);

4) recurrent tethered cord syndrome due to postoperative adhesions causing spinal cord retethering, confirmed by MRI.

The absence of these data was considered a favorable outcome.

Statistical data analysis. Data collection, cleaning, management, and visualization were performed using Microsoft Office Excel (2016). Statistical processing

of the data was carried out using Python (v. 3.12, Python Software Foundation, <https://www.python.org/>).

The normal distribution of quantitative data was evaluated using the Shapiro–Wilk test. In its absence, subsequent calculations were carried out using methods of nonparametric statistics, where the median was defined as the center of distribution and quartiles as the variation (Me [Q1; Q3]). The Mann–Whitney *U* test was used to compare two independent samples, and the Kruskal–Wallis test, a nonparametric alternative to one-way ANOVA, was used to compare three or more independent samples.

For normally distributed quantitative variables, mean (M) and standard deviation (SD) were calculated. When comparing the means of two independent samples, Student's *t*-test was calculated, while for three or more independent samples, a one-way analysis of variance (ANOVA) was used.

Results

Analysis of surgical functional outcomes (Table 3). Surgical outcomes were favorable in 92 (76.7%) patients and unfavorable in 28 (23.3%) patients.

An analysis of the types of surgical procedures performed revealed statistically significant differences in adverse outcome rates depending on the type of surgery.

Redetethering was associated with a higher risk of adverse outcomes, whereas shortening osteotomy demonstrated a statistically significantly better outcome.

Nosological structure. An analysis of the baseline diagnosis structure revealed no statistically significant differences between the study groups regarding the types of dysraphism, the Sharrard neurosegmental level of impairment [11] (Table 4), and the nosological structure. (Table 5; $p = 0.293$).

When analyzing each type of diagnosis individually (meningocele, meningo-myelocele, meningomyelomyloradiculocoele, and lipomeningocele), no statistically significant differences were found.

Table 3

Functional outcomes across groups, n (%)

Variables	All ($n = 120$)	Favorable (0); $n = 92$	Unfavorable (1); $n = 28$	p
Group 1	53 (44.2)	36 (39.0)	17 (61.0)	0.044
Group 2	27 (22.5)	25 (27.0)	2 (7.0)	0.036
Control	40 (33.3)	31 (34.0)	9 (32.0)	1.000

Number of surgeries. No statistically significant differences were observed between the groups regarding the number of surgical interventions for tethered spinal cord syndrome ($p = 0.958$). Out of 120 patients, spinal cord redetethering was not performed in 58 (48.3%) cases, while single detethering was executed

in 52 (43.3%) patients, and repeat (two-fold) detethering in 10 (8.3%).

In the favorable outcome group, redetethering was not performed in 44 patients (48.0%), while single and repeat detethering were carried out in 40 (43.0%) and 8 (9.0%) cases, respectively. In the unfavorable outcome group, the corresponding rates were as follows:

no defixation in 14 cases (50.0%), single-stage detethering in 12 (43.0%), and two-stage detethering in 2 (7.0%).

Motor status and sensory impairment. Preoperative motor status assessment using the Ashworth scale revealed no statistically significant differences between the groups ($p = 0.472$). The rate of sensory loss also showed no difference between the groups. ($p = 0.466$; Table 6).

Pelvic organ dysfunction. Statistically significant differences were found in the types of pelvic floor dysfunction ($p < 0.001$). The control group had the highest proportion of patients with atonic bladder dysfunction (67.0 %; Table 7).

Musculoskeletal deformities. Spinal deformities were identified in 72 (60.0%) of the 120 patients evaluated. In the favorable outcome group, the prevalence of spinal deformities was 58.0%

Table 4

Group characteristics according to Sharrard neurosegmental classification [11]

Neurosegmental level	Muscle strength	Group 1 ($n = 53$)	Group 2 ($n = 27$)	Control ($n = 40$)	Total
Thoracic (T)	Absence of muscle activity in the lower extremities; inability to lift the pelvis in the supine position	0	12	5	17
L1–L2	Absence of active knee extension; hip flexor (adductor) strength $< 2/5$; pelvic elevation (3–4/5)	2	13	3	18
L3–L4	Hip flexor strength (grade 4–5); knee flexor strength (grade < 3); strength of hip extensors and abductors (grade 1–2)	16	2	15	33
L5–S1	Plantar flexor strength ($< 3/5$); knee flexor strength (3/5); hip extensor and/or abductor strength (2–3/5)	26	0	17	43
S2	Plantar flexor muscle strength (grade 4–5/5)	6	0	3	9

Table 5

Baseline diagnosis distribution, n (%)

Baseline diagnosis	All ($n = 120$)	Favorable (0); $n = 92$	Unfavorable (1); $n = 28$	p
Meningocele	33 (27.5)	29 (32.0)	4 (14.0)	0.092
Meningomyelocele	24 (20.0)	18 (20.0)	6 (21.0)	0.793
Meningomyeloradiculocele	42 (35.0)	31 (34.0)	11 (39.0)	0.653
Lipomeningocele	21 (17.5)	14 (15.0)	7 (25.0)	0.260

(53/92 patients) compared to 68.0% (19/28 patients) in the unfavorable outcome group; $p < 0.001$. No statistically significant differences in the incidence of spinal deformities were observed between the groups ($p = 0.332$; Table 8).

When analyzing lower limb pathology, statistically significant differences were found for lower leg deformity ($p = 0.019$) and hip dislocation ($p = 0.001$). Hip dislocation was observed in 39.0% of patients with an unfavorable outcome compared to

11.0% in the favorable outcome group (Table 9, Fig. 1).

MRI findings suggestive of TSCS. Analysis of MRI findings suggestive of TSCS is detailed in Table 10 and Fig 2.

The only statistically significant difference between the groups was a filum terminale thickening of 2 mm or more ($p = 0.042$), which occurred more frequently in the favorable outcome group (39.0% vs. 18.0%). Conus medullaris dystopia below the L1–L2 level was observed in 100% of patients in both

groups, which met the study inclusion criteria.

Discussion

An evaluation of 120 patients with TSCS secondary to spinal dysraphism significantly enhances the understanding of clinical and radiological criteria for this condition, as well as their prognostic value for outcomes across various surgical interventions.

The results convincingly demonstrate a paradoxical pattern: despite the initially more severe condition of patients who underwent shortening vertebroto- my, this specific group showed superior long-term functional outcomes. This phenomenon may be explained by fundamental differences in the mechanisms of action of surgical methods on the TSCS. Shortening vertebroto- my is designed to address the length discrepancy between the spinal column and the spinal cord without manipulating the neural elements directly.

In contrast, microsurgical redetethering involves direct intervention on the tethered neural structures. This procedure carries a dual risk: first, it may cause additional trauma to the already altered neural tissue; second, spinal cord mobilization can lead to the formation of new adhesions and scars, potentially resulting in recurrent tethering. Furthermore, indications for redetethering are frequently determined by expert opinion rather than well-defined criteria.

In our view, the optimal age for shortening vertebroto- my is within the first six years of life. This phase exhibits peak nervous system plasticity and adaptability, potentially explaining the enhanced functional recovery. Early relief of mechanical tension prevents the progression of secondary changes and preserves the potential for the recovery of impaired spinal cord functions.

The observed variations in the frequency of lower extremity orthopedic deformities hold substantial clinical relevance. Neurogenic hip dislocations and foot deformities, which occur significantly more frequently in the poor outcome group, may serve as clinical markers of

Table 6

Distribution of patients according to neurological status assessed by the Ashworth Scale, n (%)

Variables	All ($n = 120$)	Group 1 ($n = 53$)	Group 2 ($n = 27$)	Group 3 (control) ($n = 40$)	Pairwise comparison
No (0)	27 (22.5)	15 (28.0)	0 (0.0)	12 (30.0)	$p_{1-3} < 0.001$
Paresis (1)	48 (40.0)	20 (38.0)	5 (19.0)	23 (57.0)	$p_{2-3} < 0.001$
Plegia (2)	45 (37.5)	18 (34.0)	22 (81.0)	5 (12.0)	$p_{1-2} = 0.018$

Table 7

Distribution of patients by type of pelvic floor dysfunction, n (%)

Variables	All ($n = 120$)	Group 1 ($n = 53$)	Group 2 ($n = 27$)	Group 3 (control) ($n = 40$)	Pairwise comparison
Overactive bladder	53 (44.2)	30 (57.0)	7 (26.0)	16 (40.0)	$p_{1-3} = 0.245$
Hypotonic bladder	35 (29.2)	17 (32.0)	2 (7.0)	16 (40.0)	$p_{2-3} = 0.243$
Atonic bladder	32 (26.7)	6 (11.0)	18 (67.0)	8 (20.0)	$p_{1-2} = 0.247$

Table 8

Sagittal spinal deformities in the study cohorts, n (%)

Variables	All ($n = 72$)	Group 1 ($n = 16$)	Group 2 ($n = 29$)	Control ($n = 27$)
Grade 1 kyphosis	11 (15.20)	2 (12.50)	0 (0.00)	9 (33.33)
Grade 2 kyphosis	12 (16.30)	2 (12.50)	0 (0.00)	10 (37.03)
Grade 3 kyphosis	17 (23.20)	5 (31.25)	8 (27.50)	4 (14.80)
Grade 4 kyphosis	22 (30.00)	6 (37.50)	16 (55.17)	2 (7.40)
Hyperlordosis	10 (12.20)	1 (6.25)	5 (17.10)	2 (7.40)

Table 9

Distribution of foot deformities and hip dislocations among the study groups, *n* (%)

Variables	All (<i>n</i> = 120)	Group 1 (<i>n</i> = 53)	Group 2 (<i>n</i> = 27)	Group 3 (control) (<i>n</i> = 40)	<i>p</i>	Pairwise comparison
Total number of lower extremity deformities	70 (58.0)	16 (30.2)	27 (100.0)	27 (67.5)	<0.001*	$p_{1-2} < 0.001^*$
Without foot deformity	42 (35.0)	22 (42.0)	11 (41.0)	9 (22.0)	0.127	$p_{1-2} = 0.054$ $p_{1-3} = 0.110$ $p_{2-3} = 0.947$
Equino-cavo-varus foot deformity	48 (40.0)	7 (13.0)	15 (56.0)	26 (65.0)	<0.001*	$p_{1-2} < 0.001^*$ $p_{1-3} = 0.436$ $p_{2-3} < 0.001^*$
Equino-valgus foot deformity	12 (10.0)	10 (19.0)	1 (4.0)	1 (2.0 %)	0.016*	$p_{1-2} = 0.016^*$ $p_{1-3} = 0.776$ $p_{2-3} = 0.063$
Planovalgus deformity	18 (15.0)	14 (26.0)	0 (0.0)	—	0.004*	$p_{1-2} = 0.047^*$ $p_{1-3} = 0.090$ $p_{2-3} = 0.003^*$
Hip dislocation	20 (16.7)	7 (13.0)	4 (15.0)	—	0.472	$p_{1-2} = 0.240$ $p_{1-3} = 0.435$ $p_{2-3} = 0.844$

* Statistically significant differences.

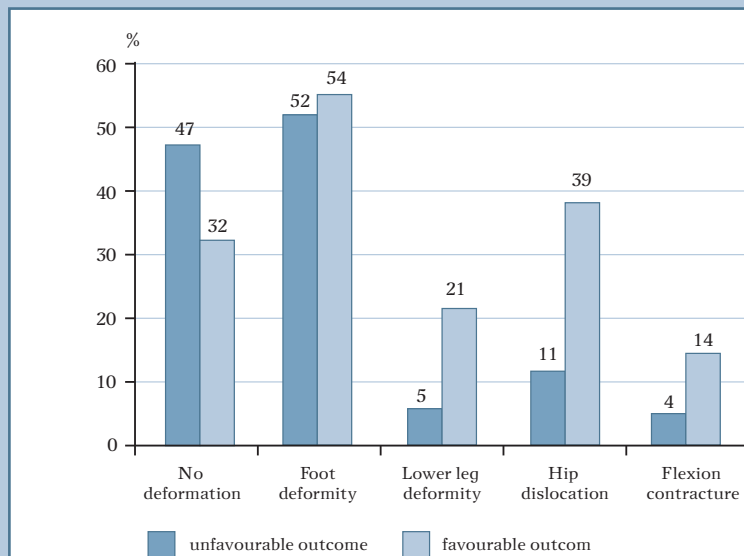


Fig. 1

Limb deformity in the study cohorts

the severity of neural structure damage, the level of motor deficit, and spasticity. As an indirect reflection of the severity of lower limb muscle denervation, they can

be used for risk stratification when planning surgical treatment.

Among the MRI features of TSCS, the paradoxical association between filum

terminale thickening and a favorable outcome is of particular interest. This may indicate that localized pathology of the filum terminale presents a more favorable prognosis.

Compared with diffuse spinal cord changes, a thickened filum terminale is more accessible for minimally invasive surgical correction and is less associated with extensive, including cicatricial, alterations.

The lack of statistically significant differences in baseline diagnoses across groups highlights that functional criteria outweigh morphological ones for predicting outcomes. This may indicate that the type of spinal dysraphism *per se* is not the primary determinant of prognosis; rather, the severity of functional impairment and the chosen treatment strategy play a pivotal role.

Methodological complexities in assessing TSCS highlighted by the study emphasize the necessity of establishing comprehensive diagnostic criteria. Clinical heterogeneity, age-related symptom dynamics, and the absence of a gold standard for diagnosis present significant challenges for a unified status assess-

Table 10

Analysis of outcomes by MR features of tensioned cord syndrome in the study cohorts, *n* (%)

Variables	All (<i>n</i> = 120)	Favorable (0) (<i>n</i> = 92)	Unfavorable outcome (1) (<i>n</i> = 28)	<i>p</i>
Hydrocephalus	37 (30.8)	29 (32.0)	8 (29.0)	0.820
Low-lying conus medullaris below the L1–L2 level	120 (100.0)	92 (100.0)	28 (100.0)	1.000
Syringomyelia	56 (46.7)	47 (51.0)	9 (32.0)	0.079
Lipoma of the filum terminale	29 (24.2)	26 (28.0)	3 (11.0)	0.077
Thickening of the filum terminale ≥ 2 mm	41 (34.2)	36 (39.0)	5 (18.0)	0.042*
Caudal regression syndrome	37 (30.8)	27 (29.0)	10 (36.0)	0.641
Cerebellar tonsillar ectopia	56 (46.7)	44 (48.0)	12 (43.0)	0.644

* Statistically significant differences.

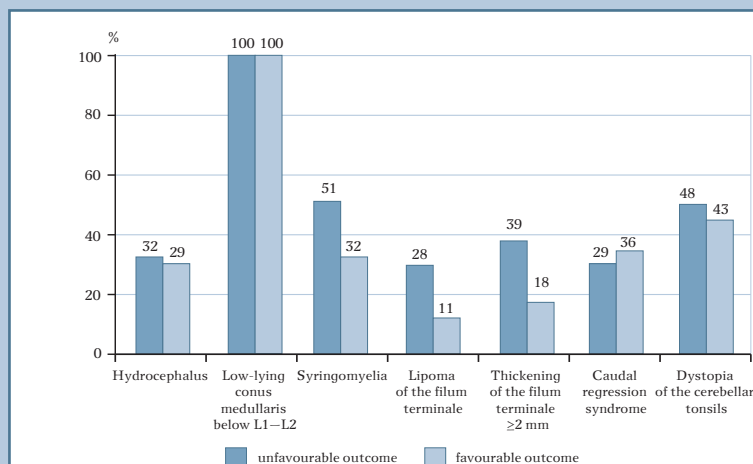


Fig. 2

MRI features of tensioned cord syndrome in the study cohorts

ment. The interdisciplinary nature of the problem requires the integration of neurological, orthopedic, urological, and neuroimaging data into a unified decision-making system.

The findings justify the need to revise traditional approaches to treating TSCS. The benefits of early shortening vertebroto my should be taken into account during the development of surgical management algorithms. Concurrently, it is crucial to develop outcome prediction models that incorporate both clinical and instrumental parameters.

Study limitations. The methodology of this study involved a strict selection of material, focusing exclusively on the diagnosis (including tension criteria) and surgical management of tethered cord syndrome. Therefore, studies on the pre-natal correction of this pathology were excluded from consideration.

These findings should be interpreted in light of the central challenge in this pathology: the lack of large-scale, high-level evidence studies and established expert consensus, which limits the representativeness of available data and the validity of the final conclusions.

Conclusion

The study yielded new data on diagnostic criteria and prognostic factors of TSCS in children with spinal dysraphism:

- a statistically significant association was identified between redetethering and the risk of adverse outcomes; however, shortening vertebrectomy demonstrated the lowest incidence of these outcomes, warranting a more thorough analysis of their causes;

- severe orthopedic deformities, including foot deformities and hip dislocations, serve as key significant prognostic factors and markers for risk stratification of adverse outcomes, reflecting the severity of neural structure impairment.

The association of filum terminale thickening with a more favorable outcome indicates that localized pathology, as opposed to diffuse changes, represents a more benign form of TSCS, which is an important consideration when planning surgical strategy.

These findings justify a revision of traditional management strategies for TSCS in spinal dysraphism, aiming to personalize and standardize treatment approaches. Methodological challenges in syndrome assessment, stemming from the heterogeneity of clinical manifestations and the absence of a diagnostic gold standard, underscore the need to develop comprehensive diagnostic criteria that integrate neurological, orthopedic, urological, and neuroimaging data.

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Received 16.12.2025

Review completed 06.05.2026

Passed for printing 13.05.2026

Additional information

Author contributions. S.O. Ryabykh: general scientific supervision, critical revision of the manuscript, refinement of formulations regarding orthopedic interventions and diagnostic criteria, and approval of the final version. A.A. Kalashnikov: drafted the original manuscript, conducted the literature review, systematized patient examination data, participated in data analysis, and prepared the final text of the article; V.S. Klimov: performed scientific editing of sections related to neurological and neurosurgical aspects, proposed revisions for interpreting data on tethered cord syndrome, and participated in the discussion of conclusions. S.A. Gorchakov: edited the clinical sections on neurosurgical treatment, provided the clinical site (Department of Neurosurgery at St. Vladimir's Children's City Clinical Hospital), and contributed comments on the methodology. All authors have approved the final manuscript (the version for publication) and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethical review. The study was approved by the Local Ethics Committee of the Veltischev Research Clinical Institute of Pediatrics and Pediatric Surgery, Moscow. (Minutes dated December 18, 2025)

Informed consent for publication. All participants provided written informed consent prior to enrollment in the study.

Sources of funding. None.

Disclosure of interest. The authors declare that they have no competing interests.

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