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Prognostic thresholds and comparative outcomes in surgical and endovascular treatment of spinal dural arteriovenous fistulas

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Abstract

Objective

Spinal dural arteriovenous fistulas (sDAVFs) are rare, debilitating vascular lesions requiring timely intervention, yet optimal criteria for selecting between surgical and endovascular techniques remain undefined. We compared surgical and endovascular treatment outcomes for sDAVFs and identified significant prognostic factors and clinically actionable thresholds.

Methods

A retrospective cohort study of 19 patients treated for sDAVFs over a 12-year period was conducted. Neurological status was assessed using the modified Rankin (mRS), McCormick, and modified Aminoff-Logue (mALS) scales preoperatively, postoperatively, three months post-treatment, and during long-term follow-up. We analyzed baseline characteristics and compared outcomes between the treatment modalities. Prognostic factors and clinically relevant thresholds were assessed using univariable, multivariable, and receiver operating characteristic curve analyses.

Results

Ten patients were treated surgically and nine endovascularly. Clinical improvement of ≥ 2 mALS points occurred in 13 (68.4%) patients. Surgical treatment resulted in greater improvement in total (4.7 vs. 1.1) and defecation (1.3 vs. 0.1) mALS scores. Shorter symptom duration, smaller feeder diameter, shorter flow void length, and higher baseline mALS scores were significant predictors of clinical recovery. Receiver operating characteristic analysis established exploratory thresholds for predicting improvement: symptom duration ≤ 405 days, total mALS > 4, mALS gait > 3, mALS micturition > 1, flow void length ≤ 145 mm, and average feeder diameter ≤ 1.05 mm.

Conclusions

Compared to endovascular therapy, surgery was associated with greater neurological recovery. The established clinical thresholds for symptom duration and radiological markers provide objective tools for prognostic counseling and managing patient expectations regarding timely intervention.

Introduction

Spinal dural arteriovenous fistulas (sDAVFs) are defined by an abnormal shunt between a radicular meningeal artery and a radicular medullary vein, resulting in arterialization of the venous system and subsequent venous hypertension. This disrupts medullary venous outflow, leading to chronic spinal cord hypoxia and congestive myelopathy. If left untreated, the resulting myelopathy is typically progressive and causes irreversible neurological deficits [1]. SDAVFs are the most common type of spinal arteriovenous malformations, comprising approximately 70% of all cases. Despite their relative frequency within this rare disease category, they often evade timely diagnosis due to their nonspecific chronic presentation and subtle radiographic appearance [2].

The pathophysiology of sDAVFs was elucidated in the 1950s via the development of catheter angiography. In 1974, *Aminoff et al.* proposed that spinal cord injury in these patients results from a reduced arteriovenous pressure gradient caused by increased venous pressure at the site of the shunt [3]. Kendall and Logue later localized the fistulous connection to the dural root sleeve between a dural branch of a segmental artery and a radicular vein [4]. Intraoperative measurements demonstrated that venous pressure within the fistula can reach 74% of systemic arterial pressure. This direct transmission of systemic pressure into the venous plexus accounts for the symptomatic flares triggered by physical exertion [5].

Treatment aims to obliterate the fistulous connection and restore normal venous drainage, either through surgical resection (Fig. 1) or endovascular embolization (Fig. 2) of the draining vein. Both approaches are well-established, yet ongoing debate persists regarding their comparative efficacy and optimal selection criteria. Advances in endovascular technology have improved accessibility and safety, yet surgical treatment remains widely regarded as more definitive in achieving permanent fistula obliteration [2, 6, 7].

While numerous studies have examined outcomes following surgical or endovascular treatment of sDAVFs [8–21], direct comparative analyses between surgical and endovascular approaches remain scarce, particularly within smaller, single-center European cohorts. Relatively few studies have systematically evaluated prognostic factors associated with clinically meaningful improvement. Among those that have, the reported findings are heterogenous and often lack consistency [10, 12, 14, 16, 18, 20, 22]. To the best of our knowledge, none of the reviewed studies has established actionable clinical and radiographic thresholds that could inform therapeutic decision-making or provide clear expectations regarding prognosis.

In this study, we present a single-center retrospective cohort of patients with sDAVFs treated over a 12-year period at the University Medical Centre Ljubljana. The primary objectives were: (1) to compare clinical outcomes between surgical and endovascular treatment approaches; (2) to identify clinical, demographic, and radiologic factors associated with favorable neurological recovery; and (3) to perform receiver operating characteristic (ROC) analysis to establish threshold values for significant prognostic indicators. The findings aim to support individualized treatment planning and highlight the importance of timely and effective intervention in patients with sDAVFs.

Materials & Methods

Study design and population

This was a single-center retrospective comparative cohort study of consecutive patients treated for sDAVFs at the University Medical Centre Ljubljana between May 2013 and May 2025. The main objectives were to compare neurological outcomes between microsurgical and endovascular treatment modalities and to identify prognostic factors associated with clinical improvement.

Eligible patients were identified from institutional surgical and endovascular procedure logs and the hospital information system using ICD-based case retrieval. Records from these sources were cross-checked and deduplicated to assemble a consecutive cohort. Patients were included if they had an angiographically confirmed sDAVF on digital subtraction angiography (DSA), underwent surgical or endovascular treatment for sDAVFs during the study period, and had a documented follow-up visit at least three months after treatment. Patients who were lost to follow-up, had insufficient follow-up duration, or were managed conservatively were excluded. Study size was determined by the number of consecutive eligible patients treated during the study period who met the inclusion criteria; no sample size calculation was performed due to the retrospective design.

The primary exposure variable for comparative analyses was treatment modality (either surgical or endovascular), as determined by a multidisciplinary neurovascular board composed of neurosurgeons, neuroradiologists, and neurologists. The principal anatomical and angioarchitectural considerations included steep radiculomedullary feeding angle and proximity of the radiculomedullary branch to the artery of Adamkiewicz, both of which could limit the safety and technical feasibility of endovascular occlusion. Endovascular therapy used commercially available embolic materials (Squid or Onyx). If embolization was considered technically unfeasible or insufficient for complete obliteration, the patient proceeded to microsurgical disconnection. In all surgical cases, laminectomy/hemilaminectomy was performed at the fistula level, and the arteriovenous shunt was interrupted and cauterized under operative microscopy. Indocyanine green fluorescence angiography was routinely used intraoperatively to guide fistula localization and confirm obliteration.

To reduce potential sources of bias, consecutive patients meeting predefined eligibility criteria were included to limit selection bias. Clinical assessments were performed using standardized institutional protocols applied uniformly across treatment groups, and functional scores were independently assigned by two reviewers. Given the limited cohort size, statistical

adjustment was kept restricted, and the observed associations are interpreted with caution, acknowledging that residual confounding cannot be excluded.

Data collection

Data for this study were extracted from hospital medical records. Neurological examinations were performed by board-certified neurosurgeons or neurologists using standardized institutional protocols, with assessments conducted at baseline and in the immediate post-treatment period during inpatient care, followed by scheduled outpatient evaluations at 3 months after treatment and at the most recent long-term follow-up visit. Documented clinical findings were independently scored by two reviewers (AP, JP) using three standardized functional scales: the modified Rankin Scale (mRS), the McCormick scale, and the modified Aminoff–Logue Scale (mALS). Radiological variables were documented by an interventional radiologist (DM). All patients underwent pre-treatment MRI and DSA, including selective catheterization of radiculomedullary arteries, to enable accurate localization of the sDAVF. Fistula occlusion was assessed by follow-up MRI or DSA performed three months after treatment.

Demographic data included patient sex, age at symptom onset and age at treatment. Clinical data encompassed presenting symptoms (type of paresis, sphincter disturbance, sensory disturbance), duration of symptoms, and consecutively assessed functional states using the mRS, mALS and McCormick scales. Radiological variables included fistula location by vertebral level, classified as cervical, upper thoracic from T1 to T6, lower thoracic from T7 to T12, or lumbar. Angioarchitectural features assessed on DSA comprised the number of arterial feeders, mean feeder diameter, length of the draining veins, drainage direction, and the presence of dilated perimedullary veins. MRI parameters included the length of T2-weighted spinal cord signal abnormality, the extent of intradural flow voids, and the presence of cord edema.

Given the retrospective nature of this analysis, no patient interventions were performed specifically for the study, and formal informed consent was not required in accordance with institutional guidelines. Our institutional review board approved this study (Ljubljana, February 21, 2022; 0120 – 26/2022/3). Clinical trial number: not applicable.

Outcome, predictors and confounders

The primary outcome was neurological improvement, defined as a ≥ 2-point reduction in total modified Aminoff-Logue Scale (mALS) score between baseline and final follow-up. Secondary scores (mALS subscales, mRS and McCormick) were used to further evaluate functional status over time. Prognostic associations were first examined in univariable analyses across all recorded candidate variables, after which variables demonstrating the strongest signal were carried forward into multivariable modeling.

Adjustment variables were selected *a priori* based on clinical plausibility and established pathophysiological considerations. In multivariable and ROC modelling, predictors were selectively adjusted for symptom duration or baseline neurological severity. Duration of symptoms was considered a potential confounder of baseline severity outcome associations given its known relationship with chronic venous congestion and potentially irreversible spinal cord injury. Baseline neurological severity, specifically the total mALS score, was treated as a covariate when evaluating temporal and radiographic predictors to account for confounding by initial disease burden. For comparisons between surgical and endovascular treatment, the baseline value of each functional outcome measure was prespecified as a covariate to account for pretreatment neurological impairment.

Statistical analysis

Statistical analyses were performed using the open-source R programming language (version 4.2.0, R Foundation for Statistical Computing, Vienna, Austria). The statistical significance level was set at $p < 0.05$ for all analyses. There were no missing data for the variables included in the analyses.

Baseline characteristics were compared descriptively between the surgical and endovascular groups. Functional scores (mALS, mRS, McCormick) were analyzed as continuous variables. Comparison of data at admission for continuous variables was performed using the Wilcoxon rank-sum test (Mann-Whitney U test). For categorical variables, we used Fisher's exact test, which is more appropriate than the chi-squared test when expected cell counts are low. For contingency tables larger than 2×2 (e.g., drainage direction), p-values were estimated using Monte Carlo simulation with 10,000 replicates to ensure valid inference [23].

To compare outcomes between surgical and endovascular treatment, we analyzed the continuous change in total mALS score using linear regression and performed exploratory analyses for secondary endpoints, including mRS, McCormick, and the mALS gait, micturition, and defecation subscores. Each functional score was estimated using linear regression models, both unadjusted and adjusted for the corresponding baseline value of the same outcome measure. Regression coefficients are reported with bias-corrected and accelerated (BCa) 95% confidence intervals derived from 2,000 bootstrap resamples.

Univariable and multivariable analyses of prognostic factors were performed using Firth's penalized logistic regression to account for small-sample bias, with 95% confidence intervals derived from the penalized profile likelihood. Predictor selection was performed in a data-driven manner, whereby variables demonstrating statistically significant association in univariable analyses were subsequently evaluated in multivariable models. Univariable analyses were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) method. Given the conceptual clustering of predictors into demographic, clinical, and imaging domains, FDR correction was applied within each predefined domain to account for multiple testing among related variables. Functional baseline scores were adjusted for the duration of symptoms pre-treatment, whereas temporal and radiographic variables were adjusted for neurological severity as specified by the baseline total mALS score. Due to the limited sample size, multivariable models were prespecified to include no more than two predictors to mitigate overfitting, and no subgroup or sensitivity analyses were performed.

To explore clinically interpretable thresholds, we performed ROC analysis using the *pROC* package in R for selected continuous predictors (symptom duration, total mALS score, mALS gait and micturition scores, length of flow voids, and average feeder diameter) against the binary improvement outcome. Analyses were adjusted for baseline neurological severity, except for mALS-based scores, which were adjusted for the duration of symptoms. Candidate cutoffs were identified using Youden's index and were used solely for exploratory post hoc dichotomization to facilitate clinical interpretability. Given the small sample size, these thresholds were considered hypothesis-generating, and no internal validation was performed.

Results

Baseline demographic, clinical and radiological characteristics

Demographic, clinical, and radiological characteristics of all patients stratified by treatment modality are presented in Table 1. A total of 19 patients were included, of whom ten underwent surgical, and nine endovascular treatment; all had complete follow-up data and were included in the final analysis. All patients presented with paresis, most commonly affecting the lower limbs (n = 18), with one case of upper-limb paresis. Dual arterial feeders were identified in two patients, whereas the remaining patients had a single feeder. Baseline demographic, clinical, and radiological characteristics were largely comparable between groups, except for a smaller average feeder diameter in the surgical cohort (mean 0.8 vs. 1.2 mm; $p = 0.012$). The median follow-up duration was 7.9 months (interquartile range 6.1–14.8 months; range 3.6–35.7 months).

Table 1: **Patient demographics and baseline characteristics**

Table 1

legend: The table summarizes key clinical variables, imaging findings, and demographic data for all included patients, as well as separately for those treated surgically and endovascularly. Categorical variables are presented as counts or proportions, while continuous variables are reported as means with corresponding 95% confidence intervals. Group comparisons were performed using Fisher's exact test or Wilcoxon rank-sum test, as appropriate. Statistical significance of differences between the two treatment groups is indicated by *p*-values. Abbreviations: mALS = modified Aminoff–Logue Scale, mALS-T = total mALS score, mALS-g = mALS gait subscore, mALS-m = mALS micturition subscore, mALS-d = mALS defecation subscore, mRS = modified Rankin Scale.

Variable		**All (n = 19)**		**Surgical (n = 10)**	**Endovascular (n = 9)**	***p***
Sex, male:female		14:5		8:2	6:3	0.629
Presenting symptoms						
Paresis, flaccid:spastic		8:11		4:6	4:5	1.00
Sphincter disturbance, yes:no		16:3		9:1	7:2	0.582
Sensory disturbance, yes:no		13:6		6:4	7:2	0.629
Age at symptom onset		61.9 [58.4–65.6]		65.5 [60.9–70.0]	58.0 [53.7–62.0]	0.050
Age at treatment		63.4 [60.1–66.8]		66.0 [61.2–70.6]	59.0 [55.2–62.7]	0.055
Duration of symptoms		294.8 [168.7–437.7]		200.7 [92.0–353.2]	399.4 [186.2–639.0]	0.288
mRS (admission)		3.6 [3.1–4.2]		3.9 [3.2–4.6]	3.3 [2.6–4.1]	0.346
McCormick (admission)		3.2 [2.7–3.6]		3.3 [2.7–3.8]	3.0 [2.3–3.7]	0.512
mALS-T (admission)		6.4 [4.9–7.8]		7.3 [5.4–9.1]	5.4 [3.3–7.4]	0.202
mALS-g (admission)		3.3 [2.7–3.9]		3.8 [3.0–4.5]	2.8 [1.8–3.7]	0.151
mALS-m (admission)		1.9 [1.4–2.4]		2.1 [1.4–2.7]	1.8 [1.0–2.4]	0.516
mALS-d (admission)		1.2 [0.7–1.7]		1.4 [0.7–2.1]	0.9 [0–3–1.6]	0.319
Location	Cervical	0	0.0%	0	0	NA
	Upper thoracic	2	10.5%	2	0	0.211
	Lower thoracic	11	57.9%	4	7	0.370
	Lumbar	6	31.6%	3	3	1.000
Number of feeders		1.1 [1.0–1.3]		1.1 [1.0–1.3]	1.1 [1.0–1.3]	1.000

Variable		All (n = 19)		Surgical (n = 10)	Endovascular (n = 9)	*p*
Average feeder diameter		0.9 [0.8–1.1]		0.8 [0.6–0.9]	1.2 [1.0–1.3]	**0.012**
Length of draining veins		57.2 [40.8–75.0]		57.1 [33.7–83.7]	57.2 [36.7–82.8]	0.935
T2 cord signal change length		185.0 [149.4–219.7]		189.0 [158.5–215]	179.3 [107.9–254.3]	0.526
Length of flow voids		147.4 [107.9–188.7]		135.0 [78.0–198.0]	161.1 [109.5–212.2]	0.099
Edema	Yes	17	89.5%	10	7	0.211
	No	2	10.5%	0	2	
Dilated perimedullary veins	Yes	17	89.5%	8	9	0.474
	No	2	10.5%	2	0	
Drainage direction	Cranial	1	5.6%	0	1	0.628
	Caudal	6	31.2%	4	2	
	Mixed	12	63.2%	6	6	

Functional outcome in surgical versus endovascular treatment

We compared the change in functional outcome scores from admission to final follow-up between surgical and endovascular treatment cohorts. The analyzed outcome metrics included the McCormick, mRS, and mALS scores, which are presented in Table 2. Patients were stratified according to the primary outcome into improved (n = 13) and not improved (n = 6) groups, which formed the basis for subsequent analyses. Overall, 15 patients improved by > 1 point, and the maximum observed improvement was 11 points. Two patients showed no change in the total mALS score, while two experienced a one-point deterioration. No procedure-related complications were observed in our cohort. In unadjusted models, surgery was associated with greater improvement in the mALS total, gait, and defecation scores. After adjustment for the corresponding baseline value of each outcome measure, the association for gait was attenuated and no longer statistically significant, whereas other associations remained significantly associated with the primary outcome.

Table 2: **Comparison of functional outcome improvements between surgically and endovascularly treated patients with sDAVFs**

Table 2

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legend: The table presents the mean change ($\varvec{\Delta}$) in neurological outcome scores from baseline to final follow-up for patients undergoing surgical (**S**) or endovascular (**E**) treatment. Per-modality differences were assessed using linear regression models, both unadjusted and adjusted for the respective baseline value of each outcome score. Regression coefficients (**β**) represent the adjusted treatment effect; negative β values indicate greater improvement after surgery, whereas positive β values indicate greater improvement after endovascular treatment. Abbreviations: CI = confidence interval, mALS = modified Aminoff-Logue Scale, mALS-T = mALS-total, mALS-g = mALS gait, mALS-m = mALS micturition, mALS-d = mALS defecation, mRS = modified Rankin Scale.

Score	_	_	**Unadjusted analysis**			**Adjusted analysis**		
	$\varvec{\Delta}$ ($\varvec{S}$)	$\varvec{\Delta}$ ($\varvec{E}$)	***p***	**β**	**95% CI for β**	***p***	**β**	**95% CI for β**
McCormick	1.4	0.89	0.334	-0.51	[-1.36–0.74]	0.470	-0.28	[-1.13–0.50]
mRS	1.7	1.22	0.442	-0.48	[-1.56–0.68]	0.874	-0.08	[-0.95–0.91]
mALS-T	4.7	1.11	**0.005**	-3.59	[-5.97 – -1.81]	**0.009**	-2.70	[-4.54 – -1.17]
mALS-g	2.0	0.56	**0.031**	-1.44	[-2.64 – -0.38]	0.134	-0.82	[-1.83–0.24]
mALS-m	1.4	0.44	0.076	-0.96	[-1.85–0.07]	**0.098**	-0.82	[-1.69–0.09]
mALS-d	1.3	0.11	**0.005**	-1.19	[-1.93 – -0.59]	0.007	-0.88	[-1.35 – -0.46]

Initial treatment success

The surgical treatment modality achieved complete angiographic obliteration in all treated cases, whereas endovascular therapy was unsuccessful in 4 of 9 patients (44.4%), a difference that reached statistical significance ($p = 0.033$). Endovascular treatment failure was defined as either partial occlusion or recanalization of the fistula, as determined by follow-up DSA. In our cohort, two failures were attributable to partial occlusion and two to recanalization.

Univariable and multivariable analysis

Univariable analysis of prognostic indicators is presented in Table 3. Shorter duration of symptoms prior to treatment demonstrated the strongest association with functional improvement. Several baseline clinical scores were also associated with better improvement rates, namely higher mRS, McCormick, total mALS, mALS gait, and mALS micturition scores. Among imaging variables, greater intradural flow void length and larger average feeder diameter were associated with lower odds of neurological improvement. However, neither remained statistically significant after FDR correction. Although not statistically significant, the effect of lesion location on treatment outcome varied between groups: patients who improved most frequently had lumbar or lower thoracic fistulas, whereas those without improvement had exclusively thoracic lesions.

Table 3: **Univariate analysis of prognostic indicators**

Table 3

legend: Univariate analysis of variables associated with neurological improvement, defined as a ≥ 2-point gain in the total mALS score at final follow-up. Categorical and continuous variables were compared between improved and not improved groups using Fisher's exact test. For continuous predictors, odds ratios with 95% confidence intervals were estimated using Firth's logistic regression. Variables were prespecified and grouped by data domain. The false discovery rate was controlled within each domain using the Benjamini–Hochberg procedure, and results are reported as **q**-values. Abbreviations: CI = confidence interval, mRS = modified Rankin Scale, mALS = modified Aminoff-Logue Scale, mALS-T = mALS-total, mALS-g = mALS gait, mALS-m = mALS micturition, mALS-d = mALS defecation, OR = odds ratio.

Variable	OR	95% CI for OR	*p*	*q*	Group
Sex (male:female)	0.468	[0.009–9.059]	1.0	0.6440	Demographic
Age at symptom onset	1.047	[0.934–1.196]	0.4306	0.6440	Demographic
Age at surgery	1.028	[0.915–1.169]	0.6439	0.6440	Demographic
Duration of symptoms	0.993	[0.981–0.998]	**0.0008**	**0.0064**	Clinical
Evaluation timespan	0.998	[0.995–1.001]	0.2334	0.2667	Clinical
mRS (admission)	2.512	[1.116–7.100]	**0.0247**	**0.0395**	Clinical
McCormick (admission)	3.771	[1.259–17.844]	**0.0154**	**0.0395**	Clinical
mALS-T (admission)	1.421	[1.030–2.231]	**0.0306**	**0.0408**	Clinical
mALS-g (admission)	2.360	[1.122–7.180]	**0.0211**	**0.0395**	Clinical
mALS-m (admission)	2.670	[1.155–8.055]	**0.0203**	**0.0395**	Clinical
mALS-d (admission)	1.403	[0.610–4.013]	0.4382	0.4382	Clinical
Number of feeders	0.440	[0.030–6.349]	0.5186	0.5834	Imaging
Average feeder diameter	0.027	[0.0003–0.691]	**0.0276**	0.2208	Imaging
Length of draining veins	1.002	[0.980–1.029]	0.8374	0.7915	Imaging
T2 cord signal change	0.151	[0.001–2.322]	0.1907	0.5593	Imaging
T2 cord signal change length	1.005	[0.995–1.017]	0.2972	0.5926	Imaging
Length of flow voids	0.988	[0.972–0.999]	**0.0242**	0.1240	Imaging
Edema (yes:no)	0.440	[0.030–6.349]	0.5186	0.5834	Imaging
Dilated perimedullary veins (yes:no)	2.826	[0.189–413.5]	0.4865	0.5834	Imaging
Drainage direction (up:down:mixed)	/	/	0.3959	0.5350	Imaging

Significant variables identified in univariable analysis were subsequently tested in two-variable models to limit overfitting while exploring whether their associations with outcome persisted. The results of multivariable analysis are presented in Table 4. In the adjusted models, only shorter duration of symptoms and a smaller average feeder diameter were associated with a higher likelihood of clinical improvement. No functional score remained significant after adjustment for duration of symptoms, although the mALS micturition subscore approached the significance threshold.

Table 4: **Multivariate logistic regression model for predictors of clinical improvement**

Table 4

legend: The table presents adjusted associations between baseline variables that were significant in univariate analysis and clinical improvement. Baseline functional scores (mRS, McCormick, total mALS, gait, and micturition subscores) were adjusted for duration of symptoms, whereas duration of symptoms and radiographic parameters (average feeder diameter and length of flow voids) were adjusted for baseline neurological severity as defined by the total mALS score at admission. Analyses were performed using Firth's penalized logistic regression. Abbreviations: CI = confidence interval, OR = odds ratio.

Baseline predictor	Adjustment	OR	95% CI for OR	*p*
mALS total	duration of symptoms	1.492	[0.909–153.4]	0.126
mALS gait		2.231	[0.741–141.1]	0.167
mALS micturition		2.276	[0.997–3457.5]	0.051
mRS		2.327	[0.719–29.2]	0.162
McCormick		3.220	[0.684–146.4]	0.142
Duration of symptoms [days]	baseline mALS total score	0.993	[0.930–0.998]	**0.004**
Length of flow voids [mm]		0.992	[0.978–1.00]	0.199
Average feeder diameter [mm]		0.022	[0.0–0.827]	**0.038**

Prognostic threshold and dichotomized outcome analysis

To determine clinically relevant thresholds predictive of postoperative improvement, we performed ROC analysis on key baseline variables, namely symptom duration, total mALS score, mALS gait and micturition scores, and length of flow voids, presented in Table 5. We then dichotomized each variable at its optimal cutoff threshold and evaluated the association with clinical improvement using Firth's penalized logistic regression, presented in Table 6. Overall, shorter duration of symptoms (≤ 405 days), a higher baseline micturition mALS subscore (> 1), and a smaller average feeder diameter (≤ 1.05 mm) emerged as significant dichotomized predictors of neurological improvement in our cohort, persisting even after adjustment for baseline neurological severity and symptom duration (as applicable). In contrast, although higher baseline disability (total mALS > 4), more severe gait impairment (mALS gait > 3), and shorter flow void length (≤ 145 mm) were associated with more favorable crude improvement rates, these variables showed weaker and less consistent prognostic contribution after adjustment.

Table 5

Prognostic threshold analysis for symptom duration, mALS total at admission, mALS gait at admission, and length of flow voids.

Table 5

legend: Each variable was tested for its power to differentiate clinical improvement status. The table includes the AUC, 95% confidence intervals for the AUC, the optimal cutoff determined by Youden's index, and the corresponding sensitivity and specificity for each threshold. Abbreviations: AUC = area under curve, CI = confidence interval, mALS = modified Aminoff-Logue Scale.

Variable	AUC	95% CI	Optimal cutoff	Sensitivity	Specificity
Symptom duration (days)	0.923	[0.765–1.0]	405.5	1.000	0.830
mALS total at admission	0.801	[0.581–1.0]	4	0.846	0.667
mALS gait at admission	0.821	[0.633–1.0]	3	0.692	0.833
mALS micturition at admission	0.801	[0.559–1.0]	1	0.923	0.667
Length of flow voids (mm)	0.700	[0.395–1.0]	145	0.692	0.833
Average feeder diameter (mm)	0.769	[0.635–1.0]	1.05	0.769	0.833

Table 6: **Clinical improvement rates and prognostic strength of dichotomized predictors based on ROC thresholds.**

Table 6

legend: Each baseline variable was dichotomized using its optimal cutoff and evaluated for association with neurological improvement. The table reports group sizes (N), improvement rates (IR), and odds ratios (OR) with 95% confidence intervals derived from Firth's penalized logistic regression. The variables were adjusted for baseline total mALS score, except mALS-derived variables (mALS total, gait, and micturition), which were adjusted for symptom duration. Abbreviations: CI = confidence interval; IR = improvement rate; mALS = modified Aminoff-Logue Scale; OR = odds ratio.

Variable	Cutoff	N	IR (%)	95% CI for IR	OR	95% CI for OR	*p*
Symptom duration (days)	≤ 405	14	92.9	[66.1–99.8]	89.4	[4.30–1.7×10^6]	**0.0014**
	> 405	5	0.0	[0.0–52.5]			
mALS total	≤ 4	6	33.3	[4.3–77.7]	0.03	[0.00–1.40]	0.0808
	> 4	13	84.6	[54.6–98.1]			
mALS gait	≤ 3	9	44.4	[13.7–78.8]	0.13	[0.00–2.31]	0.1595
	> 3	10	90.0	[55.5–99.7]			
mALS micturition	≤ 1	5	20.0	[0.5–71.6]	0.04	[0.00–0.81]	**0.0373**
	> 1	14	85.7	[57.2–98.2]			
Length of flow voids (mm)	≤ 145	10	90.0	[55.5–99.7]	5.52	[0.65–71.30]	0.1178
	> 145	9	44.4	[13.7–78.8]			
Average feeder diameter (mm)	≤ 1.05	11	90.9	[58.7–99.8]	15.1	[1.48–571.0]	**0.0202**
	> 1.05	8	37.5	[8.5–75.5]			

Discussion

This study presents a comprehensive analysis of baseline characteristics, treatment outcomes and prognostic indicators in patients with sDAVFs treated either surgically or endovascularly at a single tertiary center over a 12-year period, comprising a cohort of 19 patients. We found that microsurgical treatment was associated with higher initial occlusion rates and greater functional improvement compared with endovascular therapy after adjustment for baseline neurological status. Shorter symptom duration and greater baseline neurological impairment were associated with improved postoperative recovery. Exploratory ROC analyses identified potential prognostic thresholds for symptom duration, mALS subscores, feeder diameter, and length of flow voids that may assist future risk stratification. To our knowledge, this is the first study to propose potentially actionable prognostic cutoffs that may inform future treatment decisions, prognostic assessments, and patient stratification.

A methodological distinction from prior studies is that we defined a 2-point improvement in mALS score as the threshold for meaningful functional recovery in our regression analyses, whereas most previous reports relied on a 1-point change. Although a 1-point difference is often cited as the minimal clinically important change in functional scores, applying that threshold in our cohort would have produced a highly imbalanced distribution, with only three patients classified as not improved. Using a stricter, 2-point cutoff therefore reinforced statistical stability and comparability between groups while capturing a more robust degree of neurological recovery.

Baseline demographic, clinical and radiological characteristics were balanced between the surgical and endovascular groups, indicating that the cohorts were broadly comparable at study entry, except for average feeder diameter. This divergence aligns with prior literature and reflects preferential selection of embolization for a technically favorable vascular anatomy [24].

Surgical treatment achieved a significantly higher initial treatment success rate compared to endovascular treatment, as has been proven by others [7, 9, 16, 17]. Surgically treated patients also achieved greater functional recovery in the total mALS score and the mALS defecation subscore, even after adjustment for the corresponding baseline value of each outcome measure, consistent with previously published findings [16, 25–27]. This observation is further supported by a systematic review of 13

cohort studies, which reported a higher incidence of neurological improvement following surgery compared with endovascular therapy [28]. Some authors, however, have reported no significant difference in clinical outcomes across treatment modalities in mALS improvement [9, 12, 29]. Despite the consistent signal favoring surgery in many series, it is important to emphasize that endovascular therapy remains a valuable and effective treatment option, particularly in anatomically favorable fistulas. Modern liquid embolics, notably Onyx and N-butyl cyanoacrylate, can achieve durable occlusion when the arterial feeder is accessible and the draining vein can be safely penetrated. Authors have highlighted that, in selected cases, endovascular treatment provides rapid symptom stabilization with low procedural morbidity and obviates the need for laminectomy, which may be less suitable in elderly or medically fragile patients [30, 31]. Advances in intraoperative imaging have further strengthened the role of embolization: high-resolution 3D C-arm cone-beam CT allows detailed visualization of the fistulous point, venous drainage pattern, and microcatheter position, thereby improving the precision of embolic delivery and reducing the risk of incomplete occlusion or inadvertent venous compromise.

Our analysis supports previously reported univariable predictors of postoperative improvement, namely greater baseline neurological impairment on the mALS scale [10, 12, 16, 18, 22, 30–32] and a shorter symptom duration [10, 16, 18], emphasizing the importance of early diagnosis and prompt intervention. These newer findings are a stark contrast to earlier literature, which described severe neurological dysfunction as an unfavorable prognostic indicator [20, 33, 34]. These conflicting observations highlight the importance of follow-up duration on prognostic interpretation, as longer follow-up periods may introduce competing risks such as age-related neurological decline and comorbidities.

In line with *Peng et al.*, univariable analysis results obtained on our cohort suggest that more extensive flow voids, which reflect the extent of intradural venous congestion and have been sparsely researched in other studies, may be associated with limited neurological improvement [2]. Similarly, larger average feeder diameter was associated with poorer recovery, a finding that likely reflects anatomy-driven treatment selection, given that patients with smaller feeder diameters were more frequently treated surgically and surgical treatment was associated with superior functional outcomes. After FDR correction within the imaging variable subgroup, neither flow void length nor mean feeder diameter remained statistically significant, likely reflecting intercorrelation among imaging variables.

In multivariable models, shorter symptom duration remained associated with better improvement after adjustment for baseline total mALS score, indicating that timing captures prognostic information not fully reflected by the admission neurological score, as longer-standing symptoms likely mark more established myelopathy and reduced reversibility after fistula obliteration. Average feeder diameter also remained negatively associated with outcome after adjustment. All baseline functional scores lost significance after adjustment for symptom duration, indicating that their univariable prognostic signal was largely attributable to confounding by timing of presentation. Taken together, the data imply that recovery is driven not only by baseline functional status but primarily by disease chronicity, as was proven by others [6, 18]. Studies in larger cohorts have also reported additional prognostic factors, such as multiple treatments due to initial treatment failure or recurrence [18], moderate (4–7) or severe (8–11) baseline mALS score [2, 12, 20, 35], claudication [22], and pre-treatment gait function [32].

An additional contribution of this study is the application of ROC analysis to derive clinically actionable prognostic thresholds. Dichotomization at the derived thresholds demonstrated that the threshold-defined variables for symptom duration, mALS micturition subscore, and average feeder diameter remained significantly associated with the primary outcome. The loss of significance of the mALS gait subscore may reflect its correlation with chronic disease burden, as gait impairment represents the most prevalent manifestation of venous congestive myelopathy. In contrast, micturition dysfunction, which is frequently described as a later and less reversible feature of sDAVF, may capture a distinct dimension of cord involvement that is not fully explained by symptom duration alone [12, 36]. After adjustment for baseline neurological status, flow void length was no longer significant, likely because longer flow voids reflect more extensive venous congestive myelopathy and are closely correlated with baseline impairment. The total mALS score approached significance, but its apparent effect was largely captured by symptom duration. Patients with worse baseline deficits nonetheless showed larger measured gains, consistent with ceiling and floor effects inherent to functional scales. Prognosis should therefore be guided primarily by the duration of symptoms (≤ 405 days), with baseline status providing secondary context: patients presenting with total mALS score > 4, mALS gait > 3, or mALS micturition > 1 might exhibit greater room for quantifiable recovery, plausibly reflecting treatment during a still-congestive and

potentially reversible stage of venous hypertension. Conversely, minimal change in patients with low baseline mALS should not be interpreted as treatment failure, as the principal objective in this subgroup is prevention of further neurological decline.

The main limitation of this study is its nonrandomized design, as treatment allocation was determined by angioanatomic feasibility, introducing potential selection bias and residual confounding despite adjustment. Thus, modest shifts in effect size cannot be excluded. Due to the limited sample size and number of outcome events, multivariable models were restricted to a maximum of two predictors, limiting confounder control. Several predictors demonstrated wide confidence intervals, reflecting statistical imprecision. ROC analyses could not be performed separately by treatment group because of limited power. As prognostic thresholds obtained using ROC analysis were derived and evaluated within the same cohort, without internal validation, the results are subject to optimism bias and potential overestimation of discriminatory performance. These thresholds are exploratory, and the results should be interpreted cautiously as hypothesis-generating pending external validation in larger cohorts.

Conclusion

Overall, contemporary treatment of spinal dural arteriovenous fistulas is highly effective, with the majority of patients achieving angiographic obliteration and meaningful clinical stabilization or improvement when managed appropriately. Optimal outcomes depend on a multimodal treatment strategy, in which surgical and endovascular approaches are selected based on lesion angioarchitecture. Accumulating evidence, including the present study, suggests that surgical treatment is emerging as the more reliable modality for achieving durable fistula obliteration and sustained long-term functional improvement. Outcomes in sDAVFs are determined not only by treatment modality but also by diagnostic delay and the severity of venous hypertensive myelopathy at presentation, prompting identification of prognostic factors and clinically actionable thresholds consistent across surgical and endovascular cohorts. Neurological improvement may primarily be associated with treatment within 405 days of symptom onset, with worse baseline functional status (total mALS > 4, mALS gait > 3, mALS micturition > 1) and a flow void length of 145 mm or less showing secondary weaker associations with improvement. Presentation beyond these thresholds likely reflects a chronic state with irreversible structural injury. By integrating temporal, clinical, and imaging-based markers, our work helps identify individuals who remain within the window of reversibility and provides a better foundation for prognostic counseling.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

Our institutional review board approved this study (Ljubljana, February 21, 2022; 0120 – 26/2022/3).

Consent to participate

Given the retrospective nature of this analysis, no patient interventions were performed specifically for the study, and formal informed consent was not required in accordance with institutional guidelines.

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Author Contribution

Aljoša Škorjanc : conceptualization, methodology, software, formal analysis, investigation, writing – original draft. Borut Prestor : conceptualization, resources, writing – review and editing, supervision, project administration. Arne Jeglič : data curation, writing – review and editing. Jure Pešak : data curation, investigation, writing – review and editing. Dimitrij Lovrič : resources, data curation, investigation, visualization. Zoran Miloševič : data curation, investigation. Anita Resman : resources, data curation, writing – review and editing. Jana Kenda : data curation, writing – review and editing. Andrej Porčnik : conceptualization, methodology, investigation, resources, data curation, writing – review and editing, visualization, supervision, project administration.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available due to institutional and patient confidentiality restrictions.

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Figures

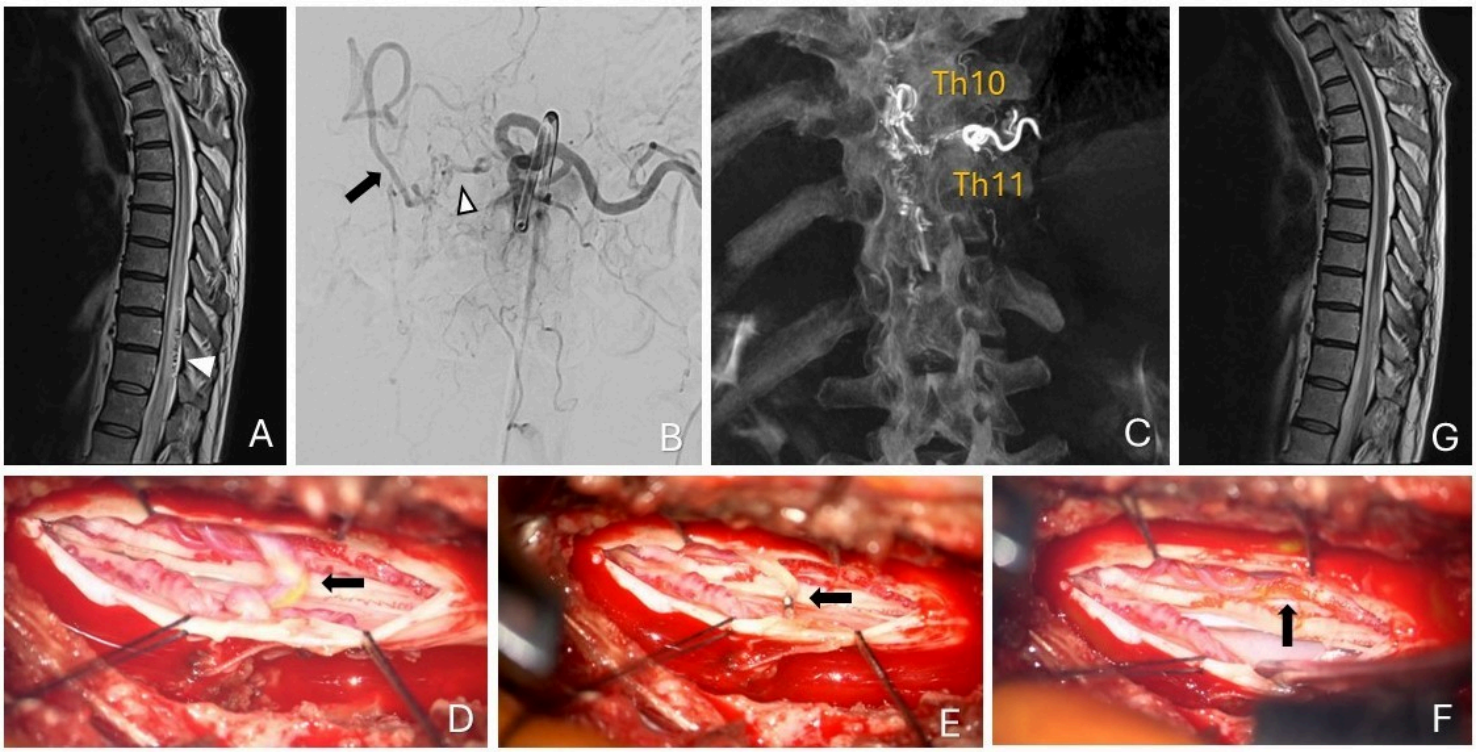


Figure 1

Case of a spinal dural arteriovenous fistula treated with microsurgery. (**A**) Sagittal T2-weighted MRI of the thoracic spine showing characteristic features with prominent hyperintense signal within the spinal cord and serpiginous flow voids seen

dorsally along the cord surface (arrowhead) representing dilated intradural perimedullary veins**.** (**B**) Digital subtraction angiography (DSA) demonstrating the arterial feeder to the fistula (arrowhead), and early opacification of dilated intradural veins (black arrow). (**C**) 3D rotational DSA image (coronal view) showing localization of the fistula between thoracic vertebral levels T10 and T11. (**D–F**) Intraoperative photographs during surgical exposure and disconnection of the fistula. (**D**) After the dural incision, the fistula was visualized (black arrow) and could be seen filling with indocyanine green in the arterial phase (yellow coloration). (**E**) Arterialized vein was coagulated and cut. **(F**) The absence of fistula and vein filling with indocyanine green indicated successful obliteration of the fistula (black arrow). (**G**) Postoperative sagittal T2-weighted MRI showed regression of spinal cord edema and decreased prominence of perimedullary flow voids, suggesting successful surgical treatment and venous decompression.

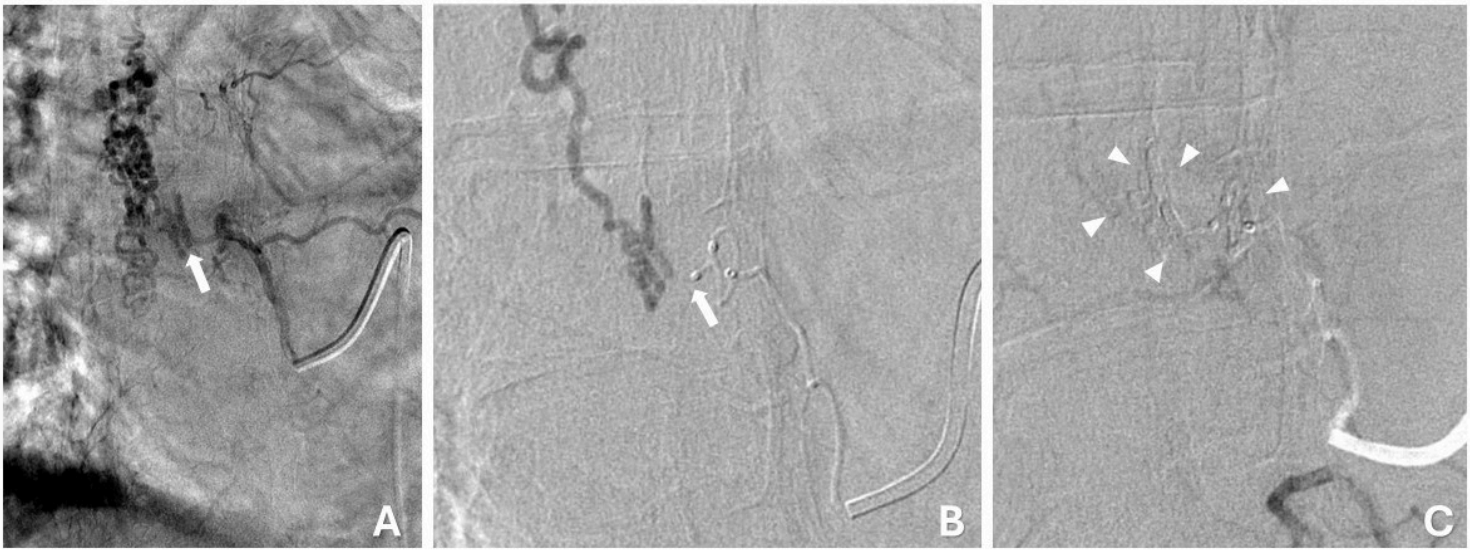


Figure 2

Digital subtraction angiography (DSA) demonstrating the angioarchitecture and treatment of an sDAVF. (**A**) Early arterial phase DSA image shows the arterial feederto the fistula (white arrow), which supplies a cluster of dilated, serpiginous perimedullary veins. (**B**) Superselective catheterization of the feeding artery provides clearer visualization of the exact site of the fistulous connection(white arrow). (**C**) Post-embolization DSA image showing complete obliteration of the arteriovenous shunt, with absence of early venous filling. The previously visualized dilated perimedullary veins (arrowheads) are no longer opacified, indicating successful endovascular treatment.