Child's Nervous System (2019) 35:945–955
https://doi.org/10.1007/s00381-019-04108-0

INVITED PAPER

Intradural spinal cord arteriovenous shunts in the pediatric population: natural history, endovascular management, and follow-up

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Received: 21 February 2019 / Accepted: 25 February 2019 / Published online: 7 March 2019

Abstract

Background Intradural spinal cord arteriovenous shunts represent a rare entity, particularly in the pediatric population, and clinical diagnosis can be challenging.

Methods We report the analysis of clinical, angioarchitectural, procedural, and follow-up data in a population of 36 children managed by our team between 2002 and 2017.

Results Hemorrhage occurred in 26 children (72%). Age at onset was 9.22 ± 3.65 years. Lesions were located at the thoracic level in 16 cases, at the cervical level in 15 cases, and the thoraco-lumbar region in 5 cases. A genetic or metameric syndrome was associated in 18 children (50%). Glue embolization provided complete occlusion in 5 children, subtotal in 7, and extensive in 14 without intraprocedural complications. We observed clinical normalization in 11 children, improvement in 11 cases, and stability in 3. Four children worsened during the follow-up, and one child died.

Conclusions Endovascular staged glue embolization performed in experienced centers is safe in the treatment of pediatric intradural spinal cord arteriovenous shunts. Clinical and neuroradiological follow-up is mandatory, especially for pediatric patients.

Keywords Spinal cord arteriovenous shunts · Intradural · Fistulas

Introduction

Spinal cord arteriovenous malformations (SCAVMs) and fistulas (SCAVFs), grouped under the term spinal cord arteriovenous shunts (SCAVSs), are considered rare lesions [1–3] which account for 5–10% of all central nervous system AVMs [4]. Pediatric SCAVSs are less frequent than adult ones, and only about 25% of pediatric SCAVMs are detected before the age of 10 [1]. Few and often incomplete data about their natural history are available in the literature because of the rarity of these lesions and their unclear clinical manifestations, leading to delayed diagnosis. MRI and MRA (magnetic resonance angiography) with novel dedicated protocols provide a more precise diagnostic tool for these lesions [5]. We report the results of our series of intradural SCAVSs in a pediatric population in order to provide complementary data about their natural history and to describe both our therapeutic protocol based on endovascular management, and the patients' follow-up.

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Materials and methods

Our series consisted of 36 consecutive children with intradural SCAVSs referred to our group between 2002 and 2017 (19 girls, 17 boys, mean age at the onset of symptoms: 9.22 ± 3.65 years). Children were either referred for treatment at our institution (32 cases) or they were managed by the referring teams following our indications (2 cases). The files of two other children were sent to us, but we had no other contacts after the discussion of the clinical and imaging files. Data on clinical onset of symptoms and angioarchitecture were therefore available for all cases, while procedural data were available for 32 children. The clinical follow-up reported in this paper only concerns the children treated by our team.

SCAVSs were sub-grouped in "nidus" (described as arteriovenous malformations or AVMs), or "fistula" (including micro- (mAFV) and macro-fistula (MAVF) as previously described in an initial publication [6]. Some patients had an association of both nidus and fistula.

Initial MRI was available in 34 children. Demographic, clinical, and anamnestic data were retrospectively collected as well as procedural data.

Concerning angioarchitecture, we defined "angioectasia" as a non-sprouting angiogenesis, characterized by the dilatation of preexisting vessels to collateralize the shunt, and "angiogenesis" as the creation of new vessels secondarily to the venous ischemia, hypoxia (under the influence of VEGF-mediated factors), or to biological phenomena related to a venous thrombosis or hematomyelia [1]. "Proximal" and "distal" aneurysms were defined according to their localization on the proximal segment of a feeder (proximal) or in a para- and intra-intralesional position (distal).

As far as the results of the embolization are concerned, we defined as complete cure a 100% occlusion of the malformation and a sub-total cure a 75–99% occlusion. A 50–75% mastering of the shunt corresponded to an extensive occlusion, while shunts occluded to less than 50% were noted as partial treatments. All treated and not totally cured children are monitored and are (potentially) considered for further treatments.

Statistical analysis

Chi-squared and Fisher's exact tests were used to assess any significant difference between non-categorical variables, and the Mann–Whitney U test was used to evaluate the differences for mean variables. p value < 0.05 was considered statistically significant.

Results

Baseline data and demographics are summarized in Table 1. Results according to the type of angioarchitecture are summarized in Table 2.

A nidus-type angioarchitecture was found in 18 children (50%) and a fistulous-type in 16 cases: 8 children with mAVF (22.2%), 5 with a single MAVF (13.9%), and 3 with mAVF and MAVF associated (8.4%). In two cases (5.5%), the angioarchitecture was characterized by the combination of nidus and fistulas. Multiple intradural lesions were observed in nine children (25.7%): in eight cases, these were affecting the spinal cord, and in one case, we found a radicular shunt associated with the SCAVS.

Hemorrhagic onset occurred in 26 cases (72.2%) mainly presenting with motor or sensory-motor symptoms. Sphincter dysfunction was associated in 10 cases (27.7%).

Table 1 Demographics

No. of children	36
Females, *n* (%)	19 (52.7%)
Age	
At onset of symptoms (median ± SD)	9.22 ± 3.65
At consultation (median ± SD)	10.44 ± 3.36
Average follow-up duration, months (range)	51.8 (1–228)
Associated syndrome, *n* (%)	18 (50)
Cobb's	*11 (30.5)*
HHT	*5 (13.8)*
RASA1	*1 (2.7)*
Parkes Weber	*1 (2.7)*
Scoliosis, *n* (%)	6 (16.6)
Hemorrhagic presentation, *n* (%)	26 (72.2)
Hematomyelia	*20 (55.6)*
SAH	*6 (16.6)*
Clinical onset	
Motor symptoms only	15 (41.6)
Sensory symptoms only	4 (11.1)
Sensory-motor associated	15 (41.6)
Other neurological manifestation	2 (5.5)
Associated sphincter troubles	10 (27.7)
Improvement before treatment, *n* (%)	27 (75)
Pre-treatment Karnofsky score, median	80
Localization, *n* (%)	
Cervical	15 (41.6)
Thoracic	16 (44.4)
Thoraco-lumbar (2 conus medullaris)	5 (14)
Classification	
Intramedullary	15 (41.6)
Superficial	21 (58.4)
Multiple intradural lesions	9 (25.7)
Initial MRI available, *n* (%)	34 (94.4)
Clinical follow-up available, *n* (%)	32 (91.4)
MR follow-up available, *n* (%)	26 (72.2)

In 27 cases (75%), a clinical improvement was observed between the onset and the first treatment with a median Karnofsky score of 80.

SCAVS were localized at a thoracic level in 16 children (50%), cervical in 15 (41.6%), and thoraco-lumbar in three (8.4%).

SCAVS were superficial in 21 children (58.4%; 15 posterior and six antero-lateral) and intramedullary in 15 cases (41.6%).

Nidus-type SCAVSs (spinal cord AVMs, SCAVMs)

Among the 18 SCAVMs, 14 were intramedullary and 4 were located on the posterior surface of the cord in the thoracic and thoraco-lumbar region (Fig. 1).

Sixteen SCAVMs bled (88.8%; 12 hematomyelias and 4 SAH). Intramedullary SCAVMs presented mainly with

Table 2 Angioarchitecture of pediatric spinal cord arteriovenous shunts (SCAVSs)

	Type of shunt					Total, *n* (%)
	AVMs (*n* = 18)	Fistulous (*n* = 16)			AVM+AVF (*n* = 2)	36 (100)
		mAVF (*n* = 9)	MAVF (*n* = 5)	mAVF+MAVF (*n* = 2)		
Hemorrhagic onset	16	5	3	1	1	26 (72.2)
SAH	4	0	1	1	0	6 (16.6)
Hematomyelia	12	5	2	0	1	20 (55.6)
Angiogenesis	11	1	0	0	1	13 (36)
Angioectasia	15	5	4	1	2	27 (75)
Pseudoaneurysms	12	1	0	0	1	14 (38.8)
Associated aneurysms						
Proximal	1	0	0	0	0	1 (2.7)
Distal	6	1	0	0	0	7 (19.4)
Multiple lesions	3	3	0	2	1	9 (25.7)

mAVF micro-fistula, *MAVF* macro-fistula, *SAH* subarachnoid hemorrhage

hemorrhage: nine were hematomyelias with neurological deficits (motor, sensory, combined: depending on the localization of the bleed), and four were sub-arachnoid hemorrhages (SAH) with (two patients) or without (two patients) neurological symptoms. Only one intramedullary SCAVM is revealed by progressive symptoms secondary to venous congestion.

Three superficial SCAVMs presented with hematomyelia and one revealed by progressive motor, sensory, and sphincter deficits due to venous myelopathy.

Two children had multiple SCAVMs: in a 7-year-old boy, an asymptomatic radicular shunt was associated with a hemorrhagic intramedullary cervical SCAVM; in a 14-year-old boy, multiple multimyelomeric superficial AVMs were detected on the conus medullaris associated with sensory and motor symptoms.

Sphincter problems occurred in two children with SCAVMs both presenting with hematomyelia.

Spontaneous clinical improvement was observed in 14/18 children (in 12 cases after a hemorrhagic onset). All four children who remained disabled harbored intramedullary SCAVMs.

Isolated macro-fistulas

All five MAVFs were superficial to the cord and were associated with hereditary hemorrhagic telangiectasia (HHT) in this series (Fig. 2). Three MAVFs were posteriorly located on the thoracic cord, and two were anterior (one thoracic and one thoraco-lumbar).

Hemorrhage occurred in three of the five MAVFs (one anterior thoracic with SAH, two posterior thoracic with hematomyelia).

Progressive deficits occurred in two patients (one posterior thoracic and one anterior thoraco-lumbar MAVF).

Paraparesis was present in all patients. Additional sensory deficits were associated in two posteriorly located cases with hematomyelia. Sphincteric problems were seen in three children with hemorrhagic thoracic MAVFs.

Spontaneous clinical improvement occurred in three cases (one of them with hematomyelia) before endovascular treatment.

Isolated micro-fistulas

Single mAVFs had an equal distribution in the anterior (three cases) and posterior surface (three cases) of the cord.

Multiple lesions were seen in three children and consisted in either mono-myelomeric thoracic cord shunts (multiple mAVFs on the same myelomere) in two children, or in multi-myelomeric shunts (multiple lesions located at different levels of the cord) in an 8-year-old boy whose thoracic mAVFs were part of a Cobb syndrome and associated to a lymphatic thoraco-abdominal malformation.

All three children with an mAVF on the posterior surface of the cord (two cervical, one thoracic) bled and presented with sensory motor symptoms.

Among the three children with anterior mAVFs, one with a cervical lesion bled with hematomyelia and subsequent sensory motor symptoms while the two others with respectively thoracic and thoraco-lumbar lesions presented with progressive motor symptoms related to venous myelopathy.

Sphincter problems were observed in two children with a hemorrhagic cervical lesion and in one child with an unruptured thoracic lesion.

Pure associated sensory symptoms were observed in the child with thoracic multi-myelomeric lesions.

Six children who bled (75%) spontaneously improved clinically before the treatment.

Fig. 1 **a** MRI, sagittal plane, T2-weighted sequence. Pre-treatment evaluation of a 12-year-old boy with a hemorrhagic spinal cord AVM located on the posterior surface of the thoracic cord, presenting with hematomyelia, venous congestion, and sensory-motor symptoms. **b** Digital subtraction angiography (DSA), antero-posterior view. Injection of left Th9 intercostal artery showing the radiculopial artery (arrowhead) feeding the nidus with the associated venous drainage caudally oriented (small arrows). Note the false aneurysm (asterisk) embedded in the nidus pointing to the hemorrhagic zone that must be embolized in priority. **c** Six-month post-embolization MRI, sagittal plane, and T2-weighted sequence showing the hemorrhagic sequelae inside the spinal cord and the reduction of the venous congestion. **d** Six-month DSA control showing the occlusion of the false aneurysm, a partial disconnection of the nidus after one embolization, and the reduced visualization of the venous drainage. The treatment is still ongoing, and other embolizations have been scheduled to further disconnect the AVM. The clinical examination was normal after 2 years

Concomitant mAVF and MAVF

Two children had multiple lesions of that kind: a 10-year-old girl with a mono-myelomeric cervical lesion presented with sensory and motor symptoms secondary to cord compression by large venous ectasias and an 11-year-old girl with a RASA-1 mutation had cervical mono-myelomeric shunts revealed by SAH.

Concomitant SCAVMs and AVFs

In two children, we found an association of an AVM and mAVFs: a 13-year-old boy with a cervical intramedullary SCAVM and two mAVFs located on different myelomeres suffered from progressive symptoms related to venous myelopathy; an 8-year-old girl with a SCAVM on the anterior face of the conus medullaris and an associated mAVF on the postero-lateral surface of the same myelomere bled.

In both cases, sensory motor symptoms with sphincter dysfunction were observed.

SCAVSs in associated metameric dispositions (Table 3)

In our series, 11 children (30.5%) had a Cobb syndrome [7] (5 cervical, 4 thoracic, 2 thoraco-lumbar) in which the spinal cord shunts were 5 intramedullary niduses (3 single, 2 multiple multi-myelomeric), 4 single mAVFs, and 2 multiple, multi-myelomeric mAVFs.

One child had an intramedullary nidus associated metamerically to an upper limb vascular malformation (Parkes Weber syndrome).

SCAVSs and genetics

HHT was associated with SCAVSs in five children (all MAVFs); three of them bled (two hematomyelia and one SAH). A RASA-1 mutation was detected in an 11-year-old girl with multiple cervical fistulas (both mAVFs and MAVFs) revealed by SAH. Angioarchitectural data regarding SCAVS associated with metameric syndromes and genetic diseases are summarized in Table 3.

Endovascular treatment

All endovascular procedures were performed under general anesthesia in a dedicated biplane neuroangiosuite. For all patients, a 4F femoral introducer sheath was positioned and flushed with saline. No heparin was administered during the procedures. However, in four cases, low molecular weight heparin was administered as adjunct therapy (100 UI/kg) after embolization in order to prevent venous thrombosis due to slowing of the blood flow. A 4F Cobra catheter (Terumo Corporation, Tokyo, Japan) was used for diagnostic angiography in thoracic and lumbar shunts, while a 4F vertebral catheter (Terumo Corporation, Tokyo, Japan) was used for the study of cervical shunts. A complete angiographic study of the vascularization of the shunt (lesional anatomy) and of the surrounding areas of the cord was always performed in order to determine the continuities of the anterior and posterior

Fig. 2 **a** MRI, sagittal plane, T2-weighted sequence. Pre-treatment evaluation of a 3-year-old girl with HHT and a hemorrhagic spinal cord macro-fistula located on the posterior surface of the thoracic cord, presenting with hematomyelia, diffuse spinal myelopathy, and sensory-motor symptoms. **b** Digital subtraction angiography (DSA), antero-posterior view. Injection of left Th11 intercostal artery showing the ectatic radiculopial feeder (arrowhead) of the macro-fistula with the associated venous ectasia (asterisk) and cranially oriented drainage (small arrows). **c** Intraprocedural DSA showing the selective glue embolization of the macro-fistula with occlusion of the venous ectasia. **d** Control injection in the same feeder showing occlusion of the lesion and the respect of the posterior pial network. **e** One-year MRI follow-up, sagittal plane, and T2-weighted sequence confirming the cure of the lesion and showing the thrombosis of the venous pouch (spontaneous hypersignal) with resolution of the venous engorgement. The clinical examination was normal at the 3-year follow-up

spinal arteries (regional anatomy), to understand the types and morphologies of the lesions and define the possibilities of endovascular therapeutic approaches. The intention-to-treat depended on the angioarchitecture of the lesion, and the presence of weak points considered to be a risk of bleeding or rebleeding (i.e., aneurysms, pseudoaneurysms, direct fistulas), related to the clinical symptoms the patient presented (angioclinical semiology).

The same catheters were used as guiding catheters into which Magic micro-catheters were introduced (Balt, Montmorency, France) for selective embolization. The size of micro-catheters (1.8, 1.5, 1.2 FM) was chosen according to the aspect of the feeders and of the shunt. Microguides (Hybrid .008 or .007 (Balt, Montmorency, France) or Mirage .008 (Medtronic, Minneapolis, USA) were used as support to help the endovascular navigation. All treatments were

Table 3 Angioarchitecture in associated syndromes

	Cobb (*n* = 11)	HHT (*n* = 5)	RASA-1 (*n* = 1)	Parkes Weber (*n* = 1)
AVM	5	0	0	1
mAVF	5	0	1	0
MAVF	0	5	1	0
AVM+mAVF	1	0	0	0
Angiogenesis	6	0	0	0
Angioectasia	8	4	0	0
Aneurysms				
Proximal	0	0	0	0
Distal	3	0	0	1
False	3	0	0	1
Multiple lesions	2	0	1	1
Intramedullary	5	0	0	1
Superficial	6	5	1	0

mAVF micro-fistula, *MAVF* macro-fistula, *HHT* hemorrhagic hereditary telangiectasia

performed with acrylic glue (Glubran and Glubran2, GEM, Viareggio, Italy; or Histoacryl (Braun, Melsungen, Germany)), but we performed trans-arterial coiling of a venous pouch representing the initial drainage of a cervical AVF in the child with multiple mono-myelomeric shunts and RASA-1 mutation. No intraoperative neurophysiological monitoring was used, and embolization was based on the analysis of anatomical safety points. In order to reduce the inflammatory effect of glue embolization, corticosteroids were prescribed in all cases for several days. All procedures were performed without anticoagulation, but heparin or low molecular heparin was given after the procedure in case of severe arterial spasm related to the catheterization or venous sludge, in order to avoid thrombosis.

At the end of the procedure, children were woken up by the pediatric anesthesiology team and transferred to the (neuro)pediatric intensive care unit, before reaching the (neuro)pediatric ward.

Results of embolization

No complications occurred during the procedures. The average number of sessions was 2.8, and although some lesions, in particular fistulous ones, could be cured in a single session, a stepwise and progressive approach was chosen in order to embolize the more complex lesions with risky architectures. Results are summarized in Table 4.

Eighty-one percent of all embolized children had their malformation mastered to more than 50%: (15.6% complete cure, 21.8% subtotal occlusion, 43.8% extensive occlusion). Partial embolization was reached in 18.8%, and these children were scheduled for further treatments.

All the macro-fistulas were completely embolized.

Eighty-five percent of the micro-fistulas that we treated were either cured or subtotally/extensively embolized.

Intramedullary niduses could not be completely occluded because of their anatomy and architecture of the shunt as we did not want to take irrelevant risks of damaging normal nervous tissue intermingled with the pathologic vascular network. Subtotal cure was reached in 6.2%, extensive occlusion in 62.5%, and partial occlusion in 31.3%.

Clinical and radiological follow-up

After the procedure, all the children were maintained under observation and examined by a neuropediatrician before discharge.

As most of the children came from abroad (15 different foreign countries), their clinical follow-up was mainly obtained by phone calls or letters from the referring physicians. As for our previously reported series [6], the Karnofsky scale was used for pre- and post-treatment clinical evaluation because it was well suited to the quality of life of a patient affected by a SCAVS. Any clinical impairment was recorded during the follow-up as well as any hemorrhagic event detected on MR. Clinical follow-up (average 51.8 months) was available in 30 cases (93.7% of treated children) and MR follow-up in 26 cases (72.2%). Two children were lost to follow-up.

Although some of these malformations could not be cured (specially AVMs), good clinical results were obtained in 83.2%: normal neurological examination was observed in 36.6% of children, improvement in 36.6%, and stabilization over time in 10% of our patients (Table 5).

Nine percent of children transitorily worsened after the embolization but recovered totally and rapidly under steroids and/or anticoagulation before the discharge. No permanent procedure-related morbidity or mortality occurred.

Table 4 Results of endovascular treatment performed by our team (32 children)

	AVMs	Fistulous type			AVM+mAVF	Total
		mAVF	MAVF	mAVF+MAVF		
Complete	0	1	4	0	0	5
Sub-total	1	4	0	2	0	7
Extensive	10	2	1	0	1	14
Partial	5	0	0	0	0	6

mAVF micro-fistula, *MAVF* macro-fistula

In five children (16.8%), treatment failed to stabilize the natural history of the disease. However, none of these treatments were led to their terms and all these children are waiting for further embolization. Two of them with unruptured thoraco-lumbar shunts (one AVM, one mAVF) associated with Cobb syndrome that had been revealed by progressive deficits, improved after partial embolization of about 50% of the shunt, remained stable for 18 months but secondarily, impaired spontaneously again; further embolizations have been proposed. Three children bled before treatment could be completed: an 8-year-old boy with a large and diffuse cervical AVM that had previously bled had recovered properly after five embolizations that partially occluded the shunt, but rebled while waiting for complementary treatment 1 year after the last session; a 10-year-old girl coming from a foreign country and who never came back for further treatment rebled 7 years after a first partial embolization of a thoracic AVM; a 5-year-old boy with four thoracic mono-myelomeric micro-fistulas bled from the last untreated lesion 9 months after the first endovascular session that had totally disconnected three of them. The two latter children are currently lost to follow-up.

Discussion

Demographics and clinical presentation

The natural history of pediatric SCAVS is poorly known; data from the literature are very limited, and the characteristics of the natural history of SCAVSs in children are commonly extrapolated from the data reported in the adult populations. However, the physiological differences between the adult and the pediatric population, such as the immaturity of the vascular tree and of the spinal cord in children, especially in the early pediatric population [8] make these two different populations not comparable. Thus, the natural history depends on the types of lesions, on their location, and on the age of the patient. If there are to the best of our knowledge, no reports of antenatally detected SCAVSs, some lesions have clinically revealed in neonates immediately after birth [9–11], which means that such lesions have been created very likely during pregnancy. The type of lesion affecting these patients is sometimes difficult to assess because the reports lack precise MRI or angiographic descriptions; however, it seems from the descriptions or angiograms or myelograms (in patients explored at the beginning of the 1980s) that most of these SCAVS are macro-fistulas with large venous varices. If one considers that most, if not all these MAVFs, are related to genetic diseases such as HHT or RASA-1 mutations, one can think that it is this genetic abnormality that is responsible very early for the creation of a shunt that remains "simple" from an architectural point of view. The SCAVSs reported in the infant population [12–15] are also described as being mainly fistulas. One can thus suspect that these lesions are mostly linked to an underlying genetic disease that reveals very early with these spinal cord vascular manifestations [12]. The review of the literature shows that the symptoms of SCAVSs in neonates are most often unrelated to hemorrhage, which points to the fragile equilibrium existing between the immature cord and the pathological vascular system and that the cord cannot compensate properly its compression or congestion by the dilated veins.

Table 5 Clinical follow-up

Occlusion grade	Total	Normal	Improvement	Stability	Worsening	Died	Hemorrhage	Lost to follow-up
100%	4	2	1	1	0	0	0	1
75–99%	7	4	3	0	0	0	0	0
50–74%	13	2	5	1	4	1	1	1
< 50%	6	3	2	1	0	0	2	0
Total	30	11	11	3	4	1	3	2

Our series lacks this very early pediatric population. The mean age at presentation was 9.22 years of age, and the mean age at first consultation was 10.44, independently of the hemorrhagic onset ($p = 0.8$). This delay could be explained by the difficulty to recognize subtle clinical signs; sub-acute clinical pictures can thus initially be misdiagnosed.

We observed in our patients a slight female predominance, in contrast to what has previously been described [6], but this could be related to a bias of recruitment of our reference center and should be taken cautiously into consideration.

Hemorrhage was the most frequent event (26/36; 72.2%), with hematomyelia in 20 cases. These data are different from those in the adult population, where SAH is more frequent [6]: a possible explanation for this difference could be related to the aging and the increased fragility of the subarachnoid veins of the cord. We noted also that there was surprisingly no clear dominance of bleeds from cervical AVSs (13/16 children) compared to other localizations (11/16 in thoracic lesions and 2/3 thoracolumbar ones), differently from what has previously been reported [6, 16]. Indeed, several factors may influence this mode of revelation of the cervical AVMs:

- hemodynamics that could be like that seen in intracranial AVMs, because of its localization above the heart, where hemorrhage is one of the main presentations, while it may be different in lesions of the thoracic and thoraco-lumbar areas, which are submitted to thoracic and abdominal pressure;
- mobility of the cervical spine with possible mechanical constraints;
- a biology that is perhaps different between cervical vessels that are created by intersegmental anastomoses creating vertically oriented vessels and those thoracic and lumbar that are initially segmental and horizontal.

However, pediatric SCAVMs being rare lesions, larger series are needed to clarify this potential difference in hemorrhagic rates between localizations on/in the cord.

In our series, the rates of hemorrhage in HHT children with spinal cord MAVFs are comparable to those previously reported [12, 17].

Although almost all patients who bled spontaneously recovered after the initial symptoms (75%), children with hematomyelia had a more severe initial clinical status on outcome than patients with SAH (median Karnofsky pretreatment scores were 80 vs 90, respectively). Similar observations have been reported by other teams [6, 18].

Among all children of this series, only three rebled before treatment (8.3%, one thoracic AVM; one cervical mAVF, and one thoracic mAVF) but this occurred between 9 and 36 months after the first hemorrhagic episode. These data in our experience confirm that hemorrhagic SCAVS exceptionally require urgent treatment, considering the delay of the rebleedings and the spontaneous recovery before the treatment, as previously published [19]. Only if a lesion is discovered in neonates or infants must treatment be carried out rapidly in order to compensate the negative effects of the shunt on an immature cord and allow proper recovery.

Angioarchitecture of the SCAVS

We observed 18 nidus-type lesions in our series, and 88.8% presented with hemorrhage (16/18), while 16 SCAVSs were fistulous lesions and were associated with a hemorrhagic onset in 56.2% of the cases (9/16) (Table 2, $p = 0.049$). Hematomyelia was observed in similar proportions in both nidus and fistulous-type lesions, respectively, in 14/18 (78%) and 8/10 (80%) cases. In the localization of the niduses within the cord parenchyma or partially invading, it explains the high rate of this type of intramedullary bleed. Hemorrhagic fistulas also create hematomyelia despite the fact that these are always superficial to the cord. This might be explained by the fact that the shunt itself is in the sub-pial space [20] and that rupture will affect the underlying vascular structures: these lesions may also drain inside the intrinsic venous drainage of the myelomere in which they are located, and hemorrhagic venous ruptures or infarctions may thus occur within the cord. Sub-arachnoid hemorrhages, which were present respectively in two SCAVMs and in one fistulous-type lesion (mAVF+ MAVF), are considered to be related to the rupture of posterior draining veins located in the subarachnoid space [8].

Pseudoaneurysms (38.8%) were only detected in hemorrhagic lesions. They pointed to the zone of the shunt that had bled and represented thus the first intention target for embolization in order to protect the patient from recurrent bleedings. In our series, these were more frequently seen in AVMs (67%) than in fistulas (6%; $p < 0.001$).

Arterial aneurysms were rarely seen in our patients (22.2%). They were mostly seen in AVMs (seven cases: five cervical and two thoracic), were most frequently distally located (only one case of proximal localization on the dysplastic arterial feeder to a complex AVM), and were found in only one fistula. The infrequent onset of aneurysms could be explained by the fact that they need time to develop, which would be less likely in a pediatric population. The fact that fistulas are the lesions with the highest flow and that aneurysms are rarely associated with these lesions makes the concept of "flow related aneurysms" in these situations doubtful. As aneurysms were more frequently seen in AVMs, one could consider that they might belong to an angiogenic manifestation that could contribute to weaken the architecture of the AVM over time. In this context of malformed vessels and altered biology and hemodynamics, aneurysms might be considered as a form of "parietal angiogenesis." In our series, the angioarchitecture was not a factor influencing hemorrhage: distal and proximal aneurysms were detected in only 27% of patients with hemorrhagic onset. A clear correlation between the presence of distal or proximal aneurysms and bleeding could thus not be proven, as reported previously [6]. Leaving them untouched would nevertheless take the risk of letting them weaken over time in a growing child. We consider that they need to be excluded from circulation by selective embolization, and when detected, they still represent targets for embolization in order to avoid potential future hemorrhages.

The real cause of bleeding in SCAVSs remains unclear. Such acute episodes may be related to biological or histological imbalances as has been described with brain AVMs [21, 22].

Pial venous reflux was observed in all SCAVS independently of their type and should be considered the cause of the signal alterations in the spinal cord on MRI related to venous myelopathy and responsible for the neurological progressive symptoms in these patients without hemorrhagic onset. The presence of venous ectasia may also contribute to the onset of symptoms by compressing the cord.

The fact that sprouting angiogenesis was more frequently associated with AVMs than fistulas ($p = 0.008$) may point to the different biological behavior of these lesions, the former being more complex in their architecture and, because of their extension, create local alterations of the normal hemodynamics in the cord, potentially leading to ischemia or hypoxia which are triggers for the development of angiogenetic vessels. Therefore, we consider that niduses are frequently characterized by a mix of both malformed and reactive vessels. When embolization of AVMs is considered, particular attention has thus to be paid to these architectures in order to avoid damage to the cord tissue, which explains why endovascular cure of AVMs is often rarely obtained.

Angioectasia was observed in 75% of the cases with a similar distribution between the AVMs (15/18 cases), fistulas (10/16 cases), and the AVM+AVF type (2/2 cases). This non-sprouting angiogenesis corresponds to the dilatation of the normal regional arteries that act as collaterals to high flow lesions; obviously, these vessels should not be occluded; they will regress after proper management of the main shunt.

SCAVSs and genetics

Two genetic mutations have been recognized in some types of SCAVSs: HHT and RASA-1 mutations. The differential diagnosis is made by clinical examination as RASA-1 patients harbor also skin capillary malformations different from the telangiectasias seen in HHT and may be associated with limb vascular malformations [23–25].

Both diseases are responsible for high flow lesions, with often similar venous ectasias. The HHT phenotypic spectrum of SCAVSs is however different from that of brain AVSs: if single MAVFs have been described in the former, in the latter, patients can be affected by multiple lesions with niduses, mAVFs, or MAVFs [26, 27]. The genetic influence on the natural history of SCAVSs is currently unknown and cannot be precisely compared to that in cerebral AVMs. In HHT brain AVMs, it is recognized that the spontaneous risk of hemorrhage is less important than in sporadic AVM [26, 28], and therefore, both therapeutic and spontaneous risks should be balanced when discussing unruptured brain AVMs. These data cannot be extrapolated to spinal cord shunts as their rarity with poor knowledge about their spontaneous natural history (as compared to brain AVSs), the difference in their vasculatures, and the environment make comparisons difficult. Furthermore, nothing is known about the spontaneous risks in RASA-1 SCAVSs. Therapeutic decisions have thus still to be taken depending on the symptoms, anatomy and architecture of the lesions.

Natural history of pediatric SCAVSs

Spontaneous evolution of SCAVSs is marked by acute episodes mostly related to hemorrhages, or to progressive symptoms due to venous myelopathy. Progressive impairments might be marked by acute symptoms from which the child might recover totally or partially according to the severity of the bleed and its localization. The symptoms will indeed be different if the patient presents a SAH that does not hurt the cord and from which he will usually recover properly, or a hematomyelia that will damage the ascending or descending tracts leaving the patient with sometimes permanent deficits that will depend on the precise location of the hematoma. Although this series is small and biased because our hospital is a tertiary reference center for SCAVSs, we found that hemorrhage was the most frequent event that occurred in pediatric SCAVSs whatever their localization. Recurrent hemorrhage was rare and never occurred within the first days or weeks after the bleed. As previously quoted [29], patients with hemorrhagic SCAVSs spontaneously recover after the acute episode and we consider that there is no need to perform any treatment in emergency. We recommend taking in charge the patient 6–8 weeks after the hemorrhage occurred, as he will then have begun to properly improve and as treatments will be easier to perform.

Treatment in non-hemorrhagic SCAVSs will be decided according to the symptoms, architecture, and anatomy of the lesion. We advocate that it should be performed rapidly when the lesion has been diagnosed as the edematous damage to the cord due to the venous myelopathy will then be reduced and will not be related to gliosis from which the child will poorly recover. Neonates and infants represent a specific population where the literature points to the severity of symptoms whatever their type. In such cases, because of these data and of the physiological immaturity of the cord, we recommend that treatment should be performed rapidly.

Treatment and follow-up

Endovascular therapy of SCAVSs in the pediatric population represents in our experience a satisfactory management that compares advantageously to surgery. It avoids trans-spinal approaches that can be hazardous in certain ages and localizations in children, allows selective catheterization of vessels that are difficult to manage (anterior spinal artery, intrinsic vasculature of the cord), and re-establishes new hemodynamic equilibriums between the AVS and the cord with satisfactory clinical results. In our experience, embolization is considered as the first treatment of SCAVSs in children. Proper recognition of the anatomy thanks to the modern angiosuites with dedicated protocols for the study of the micro-vasculature of the cord, improvement of the endovascular navigation, and precise clinical follow-ups allow us to reach (Table 5) results that are similar to those previously published [12, 19, 29, 30], with stabilization, improvement, or normalization of the symptoms, stabilization of the natural history of the lesions and low rates of bleeding or rebleeding (Table 4) with no permanent morbidity and no operative mortality. Incomplete treatments do not mean that the patient will be left alone: monitoring (both clinical and MRI/MRA) will be regularly proposed so that any change in the semiology or in the radiological pictures will bring about a new angiographic evaluation and potential further embolization. SCAVSs are indeed "living" structures that evolve over time and need to be checked for as long as they are not totally cured. We favorize this strategy which preserves the cord tissue and normal vasculature and allows satisfactory clinical outcomes.

Conclusions

SCAVSs are rare lesions, and their clinical diagnosis is difficult. MRI and MRA are the primary diagnostic modalities to discover these lesions. Although the hemorrhagic onset is frequent in this population, children often recover spontaneously and urgent treatments are not required. The endovascular treatment with staged embolization with glue is safe in experienced centers, based on precise anatomical, architectural, and clinical data. Cure of the lesions should be looked for whenever possible but cannot often be obtained, especially in AVMs. Targeted embolizations are often sufficient to obtain clinical improvement and stabilization over time. In partially treated lesions, safe long-term results are obtained if the lesions are occluded more than 50%. The more the shunt is occluded, the more stable the lesions will remain over time. In partially treated lesions, regular clinical consultations as well as neuroradiological follow-ups, usually by MRA, are mandatory to check for any changes in the patient's neurological status and angioarchitecture which would require further treatments in order to ensure the future health status of these children.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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