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Curative embolization of pediatric intracranial arteriovenous malformations using Onyx: the role of new embolization techniques on patient outcomes

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Abstract
Introduction Intracranial arteriovenous malformations (AVMs) are the most frequent cause of hemorrhagic strokes in the pediatric population. The study aim was to retrospectively assess the safety and efficacy of Onyx embolization with the intention to cure AVMs in a pediatric population.
Methods A retrospective analysis of all patients (<18 years) who underwent endovascular embolization using Onyx at our institution was conducted. The primary endpoint was the composite complete angiographic occlusion of AVM immediately after the last embolization session that had no procedure-related complication requiring emergency surgery. Secondary endpoints were angiographic occlusion rates, procedure-related complications, and clinical outcomes after treatment and at the 6-month follow-up
Results Twenty-three patients (mean age, 11.7 years) underwent a total of 45 embolization sessions. The median Spetzler-Martin grade was 3 (range 1 to 4). The primary endpoint was achieved in 19 patients (82.6 %). Complete angiographic occlusion of the AVM was obtained in 21 patients (91.3 %) immediately after embolization and at the 6-month follow-up. Embolization-related complications were observed in three patients (13 %). None of the complications resulted in permanent functional disability or death. In two patients (8.7 %), the AVM could not be completely occluded by embolization alone and the patients were referred to radiosurgery and microsurgery, respectively.
Conclusion Onyx embolization of AVM in pediatric patients with the intention to cure resulted in high occlusion rates without increasing neurological disability or death. The development of new embolization techniques and devices seems to improve the safety of Onyx embolization.

Keywords Intracranial arteriovenous malformations · Brain arteriovenous malformations · Pediatric · Children · Endovascular embolization

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Introduction

Intracranial arteriovenous malformations (AVMs) are the most frequent cause of hemorrhagic strokes in the pediatric population [1]. Although treatment indications for unruptured AVMs in the adult population have been recently discussed [2, 3], the invasive AVM treatment in the pediatric population has been indicated mainly based on the high cumulative lifetime risk of intracranial hemorrhage in children [1]. The aim of invasive AVM management is to prevent intracranial hemorrhages, which require complete exclusion of the AVM from the circulation. Complete AVM exclusion from the circulation can be achieved via microsurgical resection, endovascular embolization, radiosurgery, or using combined strategies [4–20].

The objectives of this study were to assess the safety and efficacy of endovascular embolization using Onyx as a first-line treatment in a non-selected pediatric population presenting with intracranial AVMs and to also assess the role of new devices and embolization techniques on patient outcomes.

Methods

This was a single-center retrospective study. The study protocol was approved by the institutional review board, which waived the need for written informed consent from the participants. The article was prepared accordingly, with recommendations from the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [21].

We retrospectively assessed radiological and clinical data for all pediatric patients (<18 years old) who presented with intracranial AVM and who were admitted at our institution between January 2006 and December 2014. Accordingly to our institutional multimodal strategy for treatment of AVMs, all pediatric patients presenting an AVM were firstly evaluated for endovascular embolization using Onyx with an intention to cure. If complete occlusion of AVM could not be achieved by the endovascular approach alone, then the patients were referred to microsurgical resection or to radiosurgery. We excluded all patients that presented pial or dural arteriovenous fistulas, cerebral proliferative angiopathy, or Galen vein malformations, patients that refused invasive treatment, and those that lost the follow-up or that abandoned the treatment.

We collected baseline clinical and angiographic data from patients. All patients were examined in the hospital and at the 6-month follow-up by an independent neurologist who measured neurological outcomes using the modified Rankin scale (mRS). Patients who did not return for the follow-up visit were contacted by telephone. A four-vessel digital subtracted angiography (DSA) was obtained before embolization, immediately after embolization and at the 6-month follow-up.

We assessed the role of new embolization techniques and new devices on patient outcomes during two different periods of time: before and after January 2011. In January 2011, the new detachable-tip micro-catheters were routinely available in our department [22, 23]. And, in 2011, we routinely began using new embolization techniques for the patients who presented with specific indications for using these approaches [24–29].

Embolization procedure

All procedures were performed under general anesthesia, and no heparin was infused. After complete brain angiography, 6-F guiding catheters (Guider Softip, Boston Scientific, Natick, MA, USA) with continuous saline perfusion were positioned in the cervical artery feeding the AVM. Through the guiding catheter, a DMSO-compatible microcatheter [Marathon; Medtronic-Covidien, Irvine, CA, USA), Sonic (Balt, Montmorency, France), or Apollo (Medtronic)] was advanced, with a 0.08-in. microguidewire (Mirage; Medtronic). The Onyx 18 (Medtronic) was used for all patients, and a solution of acrylic glue *N*-butyl cyanoacrylate (NBCA) [Hystoacryl (B. Braun Melsungen AG, Melsungen, Germany) or Glubran 2 (GEM, Viareggio, Italy)] and lipiodol was used for selected patients who presented hemorrhagic complications during embolization procedures. After the end of each procedure, all patients underwent brain CT scan. Corticosteroids were administrated for 5 days after the procedure. In the absence of complications, patients were extubated in the operating room and kept for 48 h in the intensive care unit under strict blood pressure control and they were discharged 5 days after the treatment.

Statistical analysis

Continuous variables were presented as the mean (range, ± SD), and the Mann-Whitney test or the Student's *t* test was used, as appropriate. Categorical variables were presented as numbers and percentages and compared among groups using chi-square or Fisher's exact tests, as appropriate. Patients were divided between two periods of time (<January 2011 and ≥January 2011) and were compared. One independent blinded statistician received all data collected for statistical analysis. The IBM SPSS Statistics software version 20.0 (Chicago, IL, USA) was used for statistical analysis. We considered p values <0.05 as significant.

Results

A total of 28 pediatric patients were screened, and 5 were excluded because they did not completed treatment or they were lost to follow-up. The parents of three patients who presented with unruptured AVMs refused any invasive treatment, and their children were clinically followed. The other two patients started embolization sessions, but both families moved to other states, and the patients were lost to follow-up at our institution. A total of 23 patients were included for analysis. The clinical and angiographic baseline characteristics of the patients are summarized in the Tables 1, 2, and 3.

Twenty-three patients (mean age, of 11.7 years) underwent a total of 45 embolization sessions (mean, 1.9 sessions per patient). A mean of 3.4 (SD = 1.9) feeding vessels was catheterized for embolization per patient. The Spetzler-Martin scores ranged from 1 to 4 (mean, 2.9; median 3, SD = 0.97). The primary endpoint was achieved in 19 of 23 patients (82.6 %). Complete angiographic occlusion of the AVM was obtained in 21 patients (91.3 %) immediately after embolization and in 22 patients (95.6 %) at the 6-month follow-up. In two patients (8.7 %), the AVM could not be completely occluded by embolization alone and the patients were referred to radiosurgery and microsurgery, respectively.

Three patients (13 %) presented with procedural complications that required emergency surgery (patients 2, 3, and 8, see Table 3). None of the complications resulted in permanent functional disability (mRS >2) or deaths at 6 months. The

Table 1 Patient's baseline clinical data dichotomized between two periods of time

	Before January 2011 (*n* = 10)	After January 2011 (*n* = 13)
Age (mean, range, SD)	12.8 (7–17, 3.2)	11 (1–17, 3.8)
Female (*n*, %)	5 (50)	7 (53.8)
Male (*n*, %)	5 (50)	6 (46.2)
Previous hemorrhage (*n*, %)	6 (60)	9 (69.2)
Parenchymal hemorrhage (*n*, %)	2 (20)	3 (23)
Ventricular hemorrhage (*n*, %)	2 (20)	2 (15.4)
Parenchymal and subarachnoid hemorrhage (*n*, %)	2 (20)	1 (7.7)
Parenchymal and ventricular hemorrhage (*n*, %)	0 (0)	3 (23)
Clinical symptoms (*n*, %)	10 (100)	13 (100)
Seizures (*n*, %)	4 (40)	6 (60)
Headache (*n*, %)	5 (45.4)	6 (46.1)
Focal neurologic deficit (*n*, %)	3 (30)	1 (7.7)

patients 2 and 3 presented acute rupture of AVM, and they were both admitted presenting right ataxia (mRS = 3) and a complete hemiparesis (mRS = 4), respectively. They both underwent embolization 2 weeks after initial symptoms. Patient 2 had a ventricular hemorrhage during embolization that was managed by immediate embolization using NBCA followed by an external ventricular drainage. Patient 2 was discharged after 10 days with ataxia (mRS = 3), and after 6 months, she presented a significant functional improvement with mild symptoms of vertigo (mRS = 1). Patient 3 had

Table 2 Patient's baseline angiographic data of AVM dichotomized between two periods of time

	Before January 2011 (*n* = 10)	After January 2011 (*n* = 13)
Spetzler-Martin grade mean, median (range, SD)	3.1, 3 (1–4, 0.99)	2.7, 3 (1–4, 1.09)
I (*n*, %)	1 (10)	1 (7.7)
II (*n*, %)	1 (10)	4 (30.7)
III (*n*, %)	4 (40)	4 (30.7)
IV (*n*, %)	4 (40)	4 (30.7)
V (*n*, %)	0 (0)	0 (0)
AVM size (cm, mean, range, SD)	2.9 (0.8–5.4, 1.39)	3.1 (1–7.4, 2.23)
<3 (*n*, %)	3 (30)	9 (69.2)
3–6 (*n*, %)	6 (60)	3 (23)
>6 (*n*, %)	1 (10)	1 (7.7)
Deep venous drainage	7 (70)	6 (46.1)
Eloquent location	9 (90)	11 (84.6)
AVM left side	1 (10)	4 (30.7)
AVM location		
Brainstem	0 (0)	0 (0)
Cerebellum	1 (10)	1 (7.7)
Corpus callosum	1 (20)	0 (0)
Thalamus	2 (20)	2 (15.4)
Basal ganglia	1 (10)	1 (7.7)
Frontal	3 (30)	6 (46.1)
Temporal	(0)	0 (0)
Parietal	1 (10)	1 (7.7)
Occipital	1 (10)	2 (15.4)
Arterial aneurysm	0 (0)	0 (0)
Nidal aneurysm	1 (10)	2 (15.4)
Venous aneurysm	1 (10)	1 (7.7)

Table 3 Individual patient's baseline data

Patient	Age/ gender	Clinical symptoms	S-M grade	AVM site/ size (cm)	Deep venous drainage	Aneurysms	Embolization sessions (*n*)	Vessels catheterized (*n*)	Complication/ treatment	AVM occlusion (immediate/6 months)	mRS (6 months)
1	11/F	VH	III	Th/1.2	Y	–	1	2	N	Y/Y	0
2	8/F	PH + SAH	III	C/2.5	Y	NA	2	2	Y^{A}/NBCA + EVD	Y/Y	1
3	13/M	PH, Left	IV	Th/3.1	Y	–	3	3	Y^{B}/EVD	N/N*	2
4	13/F	–	IV	F/5.4	Y	–	2	4	N	Y/Y	0
5	14/M	PH	IV	BG/3.5	Y	–	4	7	N	Y/Y	2
6	7/M	–	III	CC/3.6	Y	–	1	2	N	Y/Y	0
7	17/M	VH	IV	F/4.2	Y	–	2	4	N	Y/Y	0
8	15/F	–	III	P/3.2	N	VA	5	8	Y^{C}/NBCA + HE	Y/Y	2
9	15/F	–	II	O/1.8	N	–	3	6	N	Y/Y	1
10	11/M	PH + SAH	I	F/0.8	N	VA	1	3	N	Y/Y	2
11	15/M	–	II	P/2.5	N	–	2	4	N	N/Y**	1
12	12/F	PH + VH	IV	Th/3.5	Y	–	1	2	N	Y/Y	0
13	11/M	PH + SAH	III	C/1.2	Y	–	1	2	N	Y/Y	2
14	15/F	–	IV	F/7.0	Y	–	2	4	N	Y/Y	0
15	10/M	–	IV	O/6.2	N	–	4	6	N	Y/Y	0
16	12/F	VH	III	Th/2.0	Y	–	1	4	N	Y/Y	0
17	13/M	–	II	F/3.4	N	–	1	2	N	Y/Y	0
18	17/F	PH	IV	F/7.4	N	–	3	5	N	Y/Y	0
19	7/M	PH	II	F/1.0	N	NA	1	1	N	Y/Y	0
20	13/F	VH	I	F/1.8	N	NA	2	2	N	Y/Y	0
21	1/M	PH + VH	III	BG/2.0	Y	–	1	2	N	Y/Y	0
22	10/F	PH + VH	III	O/1.5	Y	–	1	1	N	Y/Y	0
23	11/F	PH	II	F/2.0	N	–	1	3	*N*	Y/Y	1

VH Ventricular Hemorrhage, *PH* Parenchymal Hemorrhage, *SAH* Subarachnoid Hemorrhage, *B* Brainstem, *C* Cerebellum, *CC* Corpus callosum, *Th* Thalamus, *BG* Basal ganglia, *F* Frontal, *T* Temporal, *P* Parietal, *O* Occipital, *NA* Nidal Aneurysm, *VA* Venous Aneurysm, *Y* Yes, *N* No, *EVD* External ventricular drainage, *HE* Hematoma evacuation, *NBCA* endovascular embolization of bleedingusing N-Butil Cyanoacrylate, *YA* diffuse ventricular hemorrhage, *YB* ventricular, parenchymal andsubarachnoid hemorrhages, *YC* parenchymal hemorrhage, *S-M* Spetzler-Martin

* Patient was referred toradiosurgery, ** Patient was referred to microsurgical resection

simultaneous ventricular, parenchymal, and subarachnoid hemorrhages during embolization that was managed by an immediate external ventricular drainage. He was discharged after 7 days presenting hemiparesis (mRS = 4), and after 6 months, he had an improvement of their hemiparesis and he was independent (mRS = 2). Patient 8 was admitted because of a seizure and an unruptured right parietal AVM (mRS = 0). Patient 8 had a large parenchymal hemorrhage during embolization that was managed by immediate embolization using NBCA followed by hematoma evacuation. He was discharged after 14 days presenting hemiparesis (mRS = 4), and after 6 months, he was independent with a left-hand paresis (mRS = 2)

Tables 3 and 4 summarize the individual outcome data and the general outcomes of patients divided into two groups based on two periods of time, respectively. We found similar occlusion rates between the two groups and a tendency toward a lower incidence of complications in the late period, after introduction of new techniques and devices (Table 4).

Figure 1 illustrates the curative Onyx embolization of a Spetzler-Martin grade IV AVM. Figures 2 and 3 represent examples of Onyx embolization of AVMs using the transvenous technique and double arterial catheterization, respectively.

Discussion

Onyx embolization of AVMs in the pediatric population

Intracranial AVMs are one of the most challenging cerebrovascular conditions in clinical care practice. Both the recent ARUBA trial and an observational study published by the Scottish Audit of Intracranial Vascular Malformations Collaborators indicated that the invasive management of unruptured intracranial AVMs resulted in worse outcomes during a relatively short-term follow-up, compared with clinical management [2, 3]. Although the clinical and scientific impact of these recent results that suggest the best invasive treatment of unruptured AVMs is under debate, the best management of pediatric AVMs remains unknown. To date, the invasive treatment of intracranial AVMs in the pediatric population has been justified mainly by the potentially large cumulative lifetime risks of intracranial hemorrhage among children who have AVMs.

Different strategies have been reported for the invasive management of pediatric AVM, including multi-modality approaches [4–8], surgical resection [9–11], radiosurgery [12–15], and endovascular embolization [16–20]. Few studies have assessed endovascular embolization using Onyx in pediatric patients with AVMs [5, 17–20]. Generally, for pediatric AVM patients, study protocols did not indicate Onyx embolization with the intention to cure. On the contrary, Onyx embolization was usually performed as a part of a pre-surgical plan developed by a multidisciplinary task force, which may explain the low cure rates using embolization alone for pediatric patients with AVMs. Data from studies evaluating pediatric patients with AVMs who were treated using Onyx embolization are described below.

In 2010, two studies reported the use of Onyx for pediatric AVMs. Thiex et al. described the use of Onyx in seven pediatric AVM patients, while Berenstein et al. reported 163 embolizations in 44 pediatric patients, with a cure rate of 20.8 % and a permanent complication rate of

Table 4 Clinical and angiographic outcomes of patients dichotomized between two periods of time

	Before January 2011 ($n = 10$)	After January 2011 ($n = 13$)	p value
Complete AVM occlusion without complications needing open surgery (n, %)	7 (70)	12 (92.3)	0.28
Complete AVM occlusion immediately after embolization (n, %)	9 (90)	12 (92.3)	1.00
Complete AVM occlusion at the 6-month follow-up (n, %)	9 (90)	13 (100)	0.43
Embolization related complications needing urgent surgery (n, %)	3 (30)	0 (0)	0.06
Parenchymal ischemia	0 (0)	0 (0)	1.00
Parenchymal hemorrhage	1 (10)	0 (0)	0.43
Ventricular hemorrhage	2 (20)	0 (0)	0.17
Subarachnoid hemorrhage	0 (0)	0 (0)	1.00
Patients treated with new embolization techniques or devices			
Patients treated by double arterial catheterization (n, %)	2 (20)	2 (15.4)	1.00
Patients treated by venous approach (n, %)	0 (0)	4 (30.7)	0.10
Patients treated with detachable tip microcatheters (n, %)	0 (0)	13 (100)	0.006
Patients who underwent radiosurgery after embolization (n, %)	1 (10)	0 (0)	0.43
Patients who underwent AVM surgery resection after embolization (n, %)	0 (0)	1 (7.7)	1.00
mRS at 6-month follow-up (median, mean) (range, SD)	1, 1 (0–2, 0.94)	0, 0.3 (0–2, 0.63)	0.47

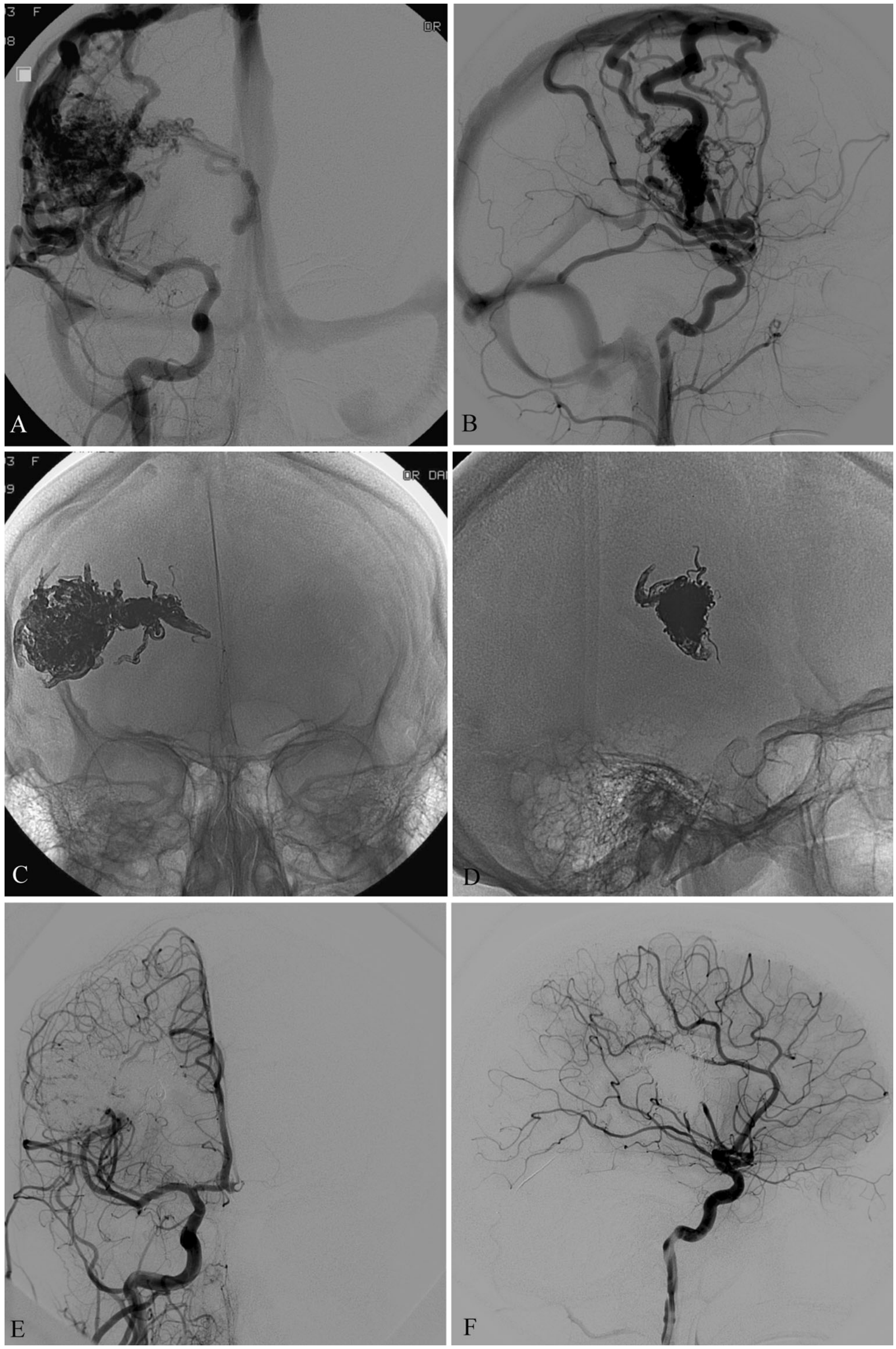

Fig. 1 **a**, **b** Digital subtracted angiography (DSA), arterial phase of right carotid artery, frontal view (**a**) and lateral view (**b**), shows a right frontal AVM Spetzler-Martin grade IV. **c**, **d** X-ray of the skull, frontal view (**c**) and lateral view (**d**), after Onyx embolization shows the final cast of Onyx. **e**, **f** DSA, arterial phase of the right carotid artery, frontal view (**e**) and lateral view (**f**), shows complete occlusion of the AVM

4.1 %. Among the 44 patients described by Berenstein et al., the Onyx was used in 12 patients and individual outcomes of this specific subgroup of patients were not reported in detail [17, 18]. In 2011, Darsaut et al. reported 195 embolization procedures in 120 patients, with a complication rate of 7.7 % and an initial cure rate of 4 %. Although the authors described using Onyx in their study's protocol, they did not report how many patients received Onyx embolization, and they did not report individual patient outcomes in this specific patient subgroup [5]. In 2012, Ashour et al. reported 51 embolization sessions in 34 pediatric AVM patients with a cure rate of 11.7 % using Onyx alone and a complication rate leading to permanent neurologic deficit of 2 % [19]. In 2013,

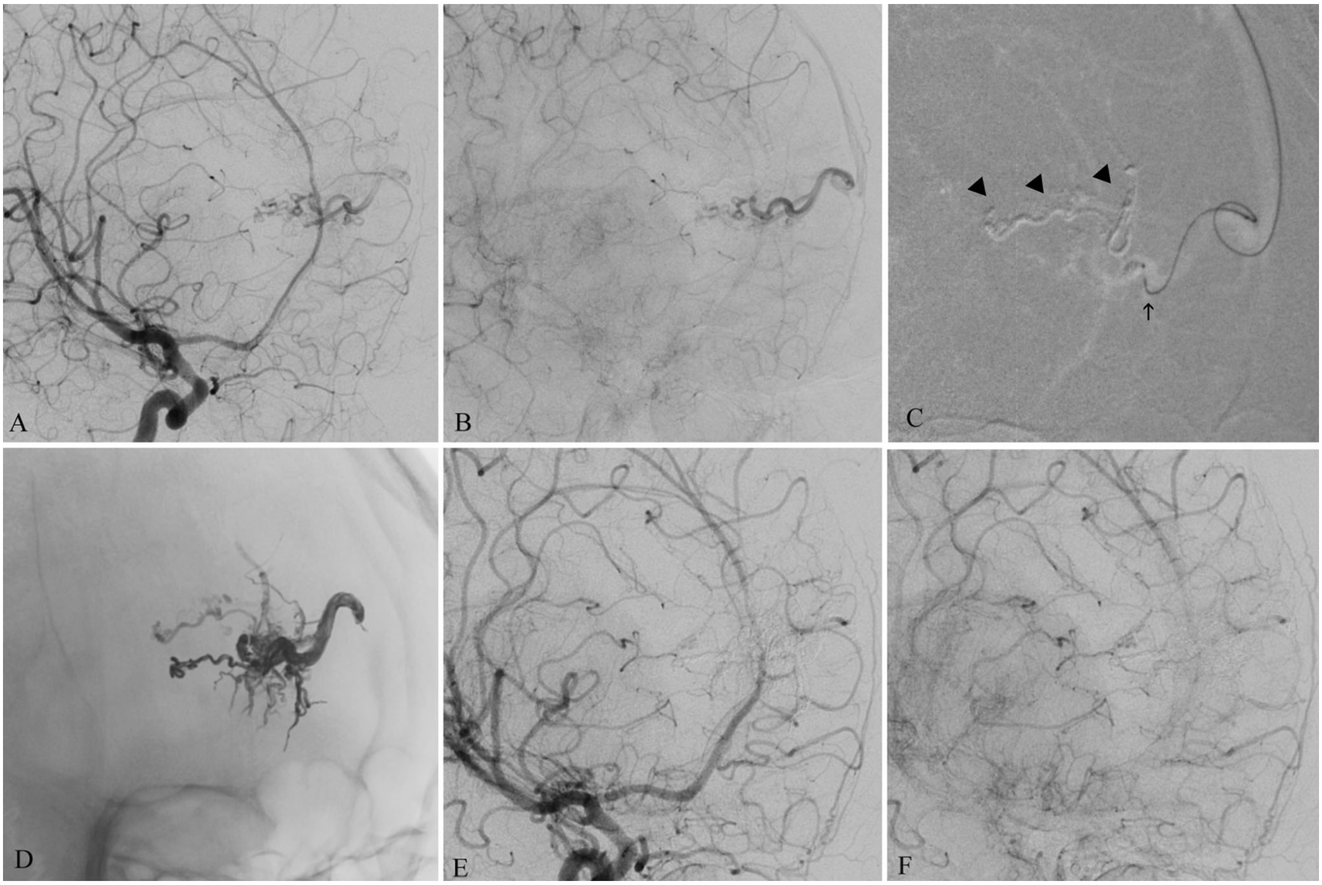

Fig. 2 **a**, **b** DSA, arterial phase of the right carotid artery, right oblique view, arterial phase (**a**) and capillary phase (**b**), shows a right frontal AVM. **c** Road map of the superficial venous circulation, right oblique view, shows catheterization (*black arrow*) of the draining vein through the superior sagittal sinus. The *black arrowhead* indicates a subtracted cast of Onyx of a previous partial embolization of the AVM. **d** X-ray of the skull, right oblique view, after transvenous embolization shows the final cast of Onyx. **e**, **f** DSA, arterial phase of the right carotid artery, right oblique view, arterial phase (**e**) and capillary phase (**f**), shows complete occlusion of the AVM

Soltanolkotabi et al. reported 38 embolizations in 25 pediatric AVMs, resulting in a complete embolization rate of 12 % and no permanent neurologic complication [20].

Onyx embolization of AVMs in the adult population

Although data on Onyx embolization in pediatric AVM patients is scarce, large studies have been published reporting results in adult patients presenting with AVMs. Recently, large series were published that assessed Onyx embolization for AVMs. The BRAVO study included 117 patients and showed a complete occlusion rate of 23.5 % and a complication rate of 9.4 % [30]. In a study published by Crowley et al., the authors reported embolization of 342 cerebral AVMs, and Onyx was the sole embolic agent used in 105 AVMs. The rate of permanent neurologic complication or death was 9.9 %, while the curative rate by embolization alone was 2.2 %. Embolization was performed as a pre-surgical treatment in 78.9 % of patients in that study [31]. Therefore, in studies where Onyx embolization was not a first-line treatment strategy, we observed similar low curative rates using embolization alone (<24 %) and similar complication rates (<10 %).

Other studies have reported results of AVMs using Onyx with a curative goal. In a study published by Katsaridis et al., the authors reported in a series of 52 patients, who completed embolization treatment, an occlusion rate of 53 % and a morbidity and mortality rate of 11 % [32]. Saatci et al. reported 607 embolizations in 350 patients. The occlusion rate was 51 %, and the morbidity and mortality rate was 8.5 % [33]. In addition, Baharvahdat et al. reported 827 embolizations in 408 patients, with an impressive occlusion rate of 70 % and the rate of permanent disability or death was 9.2 % [34]. Compared with studies where Onyx embolization had a pre-surgical role, studies where Onyx embolization had a curative goal resulted in higher occlusion rates (50–70 %) and similar complication rates (<10 %). A complication rate of 10 % is a reasonable lower complication boundary compared with the outcomes of the medical management arm of the ARUBA trial, which showed a stroke or death rate of 10.1 % and a neurological disability or death rate of 14 % [2].

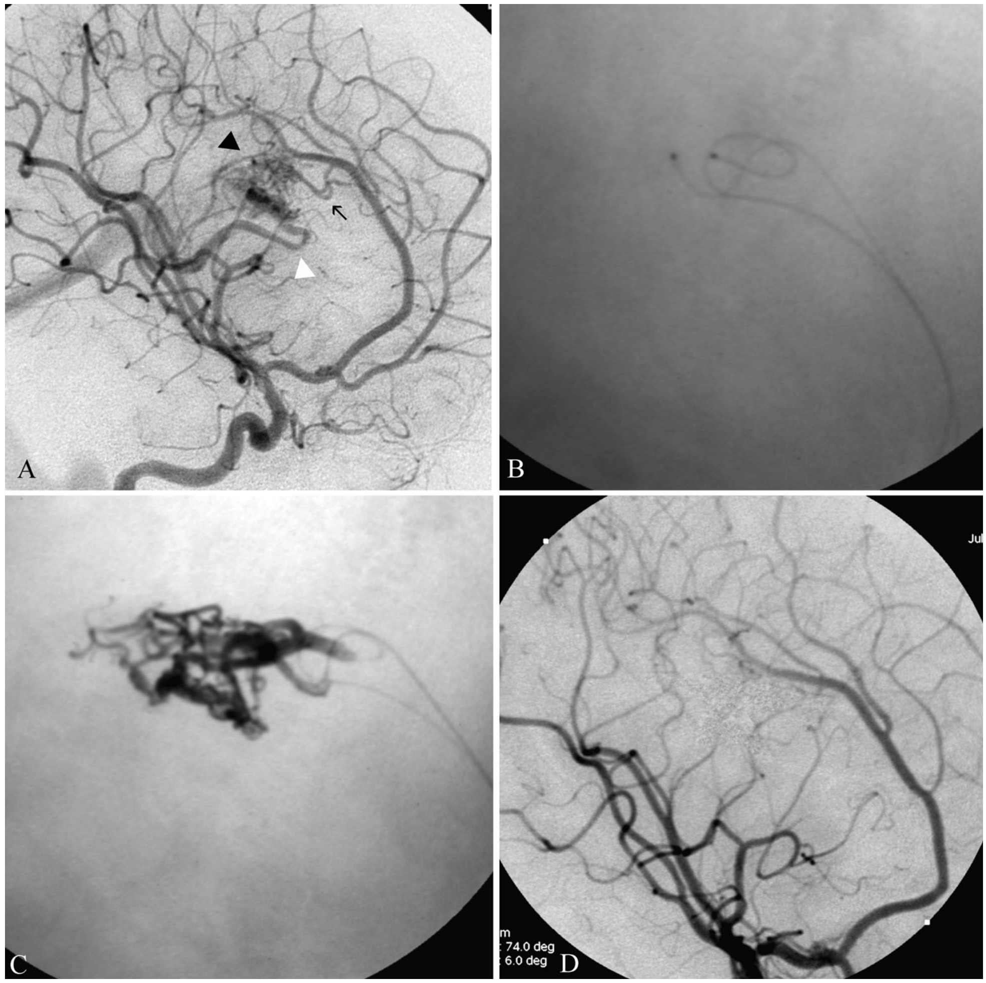

Fig. 3 **a** DSA, arterial phase of the right carotid artery, right oblique view, arterial phase, shows a right frontal AVM; the AVM is compound of a nidus (*black arrowhead*), two arterial feeders (*black arrow*), and a draining vein (*white arrowhead*). **b** X-ray of the skull, right oblique view, shows two microcatheters placed into the nidus through the two arterial feeders, ready for the simultaneous Onyx injection. **c** X-ray of the skull, right oblique view, after embolization shows the final cast of Onyx. **d** DSA, arterial phase of the right carotid artery, right oblique view, arterial phase, shows complete occlusion of the AVM

The new embolic agents, devices, and techniques for embolization of AVMs

The non-adhesive liquid embolic agents such as Onyx have been considered to be an evolution of the embolic materials for treatment of AVMs. Because of its non-adhesive characteristics and its low precipitation rate, Onyx results in more controlled and prolonged injections, which increases the probability of complete AVM occlusion. However, Onyx embolization with the intention to completely occlude the AVM may increase the risks of both ischemic and hemorrhagic complications. Intracranial hemorrhage is the most frequent complication and the first cause of neurological disability after endovascular treatment of AVMs [34]. Hemorrhagic complications have been mainly associated with the premature occlusion of the draining vein, the high volume of Onyx injected, and microwire or microcatheter perforation during AVM catheterization or at the end of embolization by an arterial tear during catheter retrieval [34]. Methods of reducing the hemorrhagic complications of endovascular AVM treatment using new embolization techniques have been recently described. The technique of double arterial catheterization with simultaneous injection of Onyx reduces the risk of an inadvertent premature occlusion of AVM draining veins before complete occlusion of the nidus is achieved. The double arterial catheterization allows complete occlusion of the nidus avoiding a hazardous premature occlusion of draining veins [24]. Another complication that may occur at the end of embolization is acute hemorrhage during the maneuver to withdraw the microcatheter. Retrieval of the microcatheter trapped by the cast of the embolic agent after embolization can cause stretching of the arterial feeder leading to vessel tear and hemorrhage. To address this issue, detachable-tip microcatheters were developed to reduce hemorrhagic risks, because during the microcatheter retrieval maneuver, the distal tip of the microcatheter will theoretically detach before high stretching forces are applied in the arterial feeder [22, 23]. However, distal and highly tortuous arterial feeders may still have a high risk of rupture during microcatheter withdrawal, even using a detachable-tip microcatheter for Onyx injection. For those patients, the security catheter technique is a strategy that improves AVM embolization safety [29]. In this technique, a second microcatheter is placed into the arterial feeder before the retrieval maneuver of the microcatheter used for Onyx injection. Therefore, the second microcatheter can promptly be used to control a potential hemorrhage.

In addition to safety improvements for endovascular AVM embolization, other new techniques may expand the percentage of AVMs that can undergo curative embolization. The transvenous embolization technique allows endovascular cure of complex intracranial AVMs with high Spetzler-Martin grades and AVMs with deep draining veins and relatively small nidus sizes [25, 26]. In addition, for some deep AVMs with recurrent arterial feeders where arterial catheterization may be extremely challenging and hazardous, the balloon-assisted microcatheter navigation technique can be used to safely achieve catheterization of the recurrent arterial feeders allowing AVM embolization [27]. Another recently described embolization strategy, the Pressure cooker technique, increases the amount of Onyx that can be injected into AVMs during a relative short period of time while simultaneously avoiding a large reflux through the arterial feeder. The authors of the pressure cooker technique argue that, compared to the standard super-selective AVM angiograms, contrast injections through a trapped microcatheter in wedge-flow conditions allow for a better visualization of nidal angio-architecture and flow compartments [28].

Study limitations

The main limitations of this study were the retrospective single-center design, the small sample size, and the lower complication rates observed, which preclude definitive conclusions on the role of new techniques and devices on the outcomes obtained. Because of the lower rate of complications (three cases), the higher rate of complications of the early treatment period (before January 2011) compared to the late period (after January 2011) could be caused by coincidence. Although we achieved a high rate of complete occlusion in a non-selected population of patients presenting with AVMs, the external validity of our results should be interpreted with caution, because the use of recent embolization techniques requires a considerable technical experience, which may be highly variable across neuro-interventional centers.

Conclusion

Onyx embolization of pediatric AVM with the intention to cure resulted in high occlusion rates without increasing neurological disability or death. The development of new embolization techniques and devices seems to improve the safety of Onyx embolization.

Compliance with ethical standards We declare that all human and animal studies have been approved by the ethics committee for research of our institution and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. We declare that the study protocol was approved by the institutional review board, which waived the need for written informed consent.

Conflict of interest We declare that we have no conflict of interest

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