Chapter

Endovascular Treatment of Cerebral Arteriovenous Malformations

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Abstract

Arteriovenous malformations (AVM) are vascular malformations composed of a network of abnormal vessels connecting directly between the artery and vein without an intervening capillary bed. Cerebral arteriovenous malformations have an incidence of 0.8–1.3 per 100.000 person years. Clinical symptoms include intracranial hemorrhage, seizure, headache, and focal neurological deficit. Annual mortality rate associated with hemorrhage is 1–5%, and 10–30% of survivors will have disability. Treatment options for cerebral AVMs include open surgery, embolization, and radiosurgery. Depending on the grade and angioarchitectural characteristics, a combination of these modalities can be used. Endovascular treatment can be performed for size and grade reduction, presurgical devascularization, size reduction before radiosurgery, targeted embolization, and as stand-alone treatment for cure. Targeted embolization can address intranidal or flow-related aneurysms and high flow arteriovenous shunts. Complications of the endovascular treatment include hemorrhage related to vessel perforation or normal pressure breakthrough phenomenon, ischemia, microcatheter retention, and other general complications associated with angiographic procedures. Mortality associated with endovascular treatment is less than 2% and permanent neurological deficit can be seen up to 2–8.9% of cases. New endovascular techniques include balloon-assisted embolization, transvenous embolization, and double microcatheter techniques like pressure cooker technique.

Keywords: cerebral arteriovenous malformation, intracranial hemorrhage, endovascular, embolization

1. Introduction

Arteriovenous malformations (AVM) are vascular malformations composed of a network of abnormal vessels connecting directly between the artery and vein without an intervening capillary bed. AVMs are thought to be congenital lesions originated from persistence of primitive arteriovenous connections [1].

1.1 Epidemiology

According to epidemiological studies, including Netherland Antilles [2], Olmsted county Minnesota [3], and New York islands [4], incidence of cerebral

arteriovenous malformations is between 0.8 and 1.3 per 100.000 person years. In addition to sporadic cases, brain AVMs can be associated with syndromes including hereditary hemorrhagic telangiectasia, Wyburn-Mason syndrome, and Sturge-Weber syndrome [5, 6].

1.2 Clinical presentation

Symptomatic brain AVMs may present with intracranial hemorrhage (50%), seizure (33%), headache (16%), or focal neurologic deficit (6%) [7]. Annual risk of bleeding of due to brain AVMs is approximately 2–4%. Risk factors increasing the odds of bleeding include prior history of intracranial bleeding due to AVM, deep location, exclusive deep venous drainage and single draining vein, intranidal aneurysm, and high intranidal pressure [7–9]. When there are three factors, risk may increase up to 34%. In patients presenting with hemorrhage, rebleeding risk in the first year is approximately 32% that decrease to 11% in subsequent years [10]. Annual mortality rate is approximately 1.5% and 10–30% of survivors have long-term disability. Neurological disability is more common in ruptured AVMs compared to aneurysm rupture due to higher likelihood of a lobar hematoma [11]. Although there is conflictive data, smaller AVMs have a higher tendency to present with hemorrhage. Spetzler et al. [12] found that 82% of smaller AVMs (<3 cm) present with hemorrhage compared to 21% of hemorrhage seen in larger AVMs (>6 cm). Ondra et al. [13] published a series of 160 symptomatic untreated AVM cases and found that 23% of the patients died during a mean follow-up of 23.7 years.

1.3 Therapeutic strategies

AVM treatment includes medical management, surgical, endovascular, and radiosurgical modalities. ARUBA, largest multicenter randomized trial to date, showed that medical management alone is superior to interventional therapy for the prevention of death and stroke in patients with unruptured AVMs [14, 15]. However, the follow-up period in this study was only 33 months, and 5-year follow-up results that will prove whether these results are persistent are yet to be published. Nevertheless, ruptured AVMs, unruptured AVMs with significant risk factors, and some symptomatic AVMs in young patients must be treated. These treatment modalities can be used as stand-alone treatment for cure, or a combination of different techniques can be used to increase the efficiency and minimize the risks associated with treatment. Although there is still no consensus on the ideal treatment, every case is evaluated specifically for its rupture risk and risks associated with its treatment. The most common grading system used to stratify the risks of surgical treatment of AVMs is the Spetzler-Martin system [16]. This system classifies the AVMs according to size, location, and venous drainage. Larger lesions, AVMs with deep venous drainage, and lesions in eloquent locations have higher surgical risk. Eloquent locations include sensorimotor cortex, visual cortex, thalamus, internal capsule, brainstem, cerebellar peduncles, and deep cerebellar nuclei. Deep venous drainage sites are straight sinus, internal cerebral veins, basal veins of Rosenthal, and precentral cerebellar veins. Spetzler and Ponce proposed a modified version of the grading system in 2011 [17].

AVMs larger than 3 cm in a non-eloquent and superficial location can be safely treated with embolization followed by surgery. AVMs larger than 3 cm with a deep or eloquent location can be embolized and then radiosurgery can be used for the ultimate cure. Smaller lesions (<3 cm) can be safely treated with surgery alone or

radiosurgery can be used as stand-alone treatment in case of eloquent or deep location. For ruptured small deeply located surgically inaccessible AVMs, embolization can be used as a stand-alone treatment for cure.

2. Endovascular treatment

The first report of embolization of an AVM was published by Luessenhop and Spence et al. in 1960 [18] who used methyl methacrylate pellets after a direct carotid puncture. Selective catheterization of the intracranial circulation with microcatheters was first described by Serbinenko et al. [19] and Kerber. Further evolution has occurred with the use of new liquid embolic agents like cyanoacrylate by Drake et al. [20] and Debrun et al. [21]. After years of embolization with N-butyl cyanoacrylate, introduction of a new agent composed of ethylene vinyl alcohol polymer (Onyx, Medtronic, Irvine, CA, USA) has changed the practice of AVMs once more.

Endovascular treatment of cerebral AVMs can be used before open surgery, before radiosurgery, for cure as a stand-alone treatment, to target the weak angioarchitectural points, or for palliative purposes. The advantages of endovascular treatment include minimally invasiveness, immediate angiographic evaluation during and after the treatment, and immediate occlusive effect. Angiography is the gold standard for the diagnosis and treatment planning for AVMs. Angiograms show the location, size, and number of arterial feeders and draining veins and locate weak points such as intranidal aneurysms, flow-related aneurysms, venous drainage stenosis, ectasia, or aneurysm of the draining veins. These angioarchitectural characteristics lead to decision on the treatment strategy for a specific AVM including surgical, endovascular, or radiosurgical techniques.

2.1 Embolization before surgical resection

Preoperative embolization reduces the blood loss during surgery and decreases surgery times. By decreasing the size of an AVM, the Spetzler-Martin grade and eventually surgical morbidity-mortality are decreased (**Figure 1**). Grade 1 and grade 2 AVMs, which are amenable to stand-alone surgery, may benefit from the embolization of the deeply located feeders. Grade 3 AVMs with deep and eloquent location can be treated with embolization preoperatively and surgical morbidity and mortality can be reduced significantly [22]. Presurgical embolization is the most beneficial for grade 3 AVMs.

2.2 Embolization before radiosurgery

Obliteration rates after radiosurgery decreases as the size of an arteriovenous malformation increases. Obliteration rate decreases from 80 to 50% when the size of the AVM increases from 2.5 to 3 cm [23]. The main aim of embolization before radiosurgery is to decrease the size of the lesion before radiosurgery [24] (**Figure 2**). AVMs larger than 3 cm can benefit significantly by embolization. A successful embolization obliterating the periphery of an AVM can help to decrease the required dose for obliteration and negative effects of the radiosurgery on the neighboring tissues [25]. If an AVM has intranidal aneurysms, these aneurysms can be embolized to decrease the bleeding risk during the latency period. Additionally, targeted embolization can be used to obliterate direct arteriovenous shunts in the arteriovenous malformations to increase the efficiency of the radiosurgery [26].

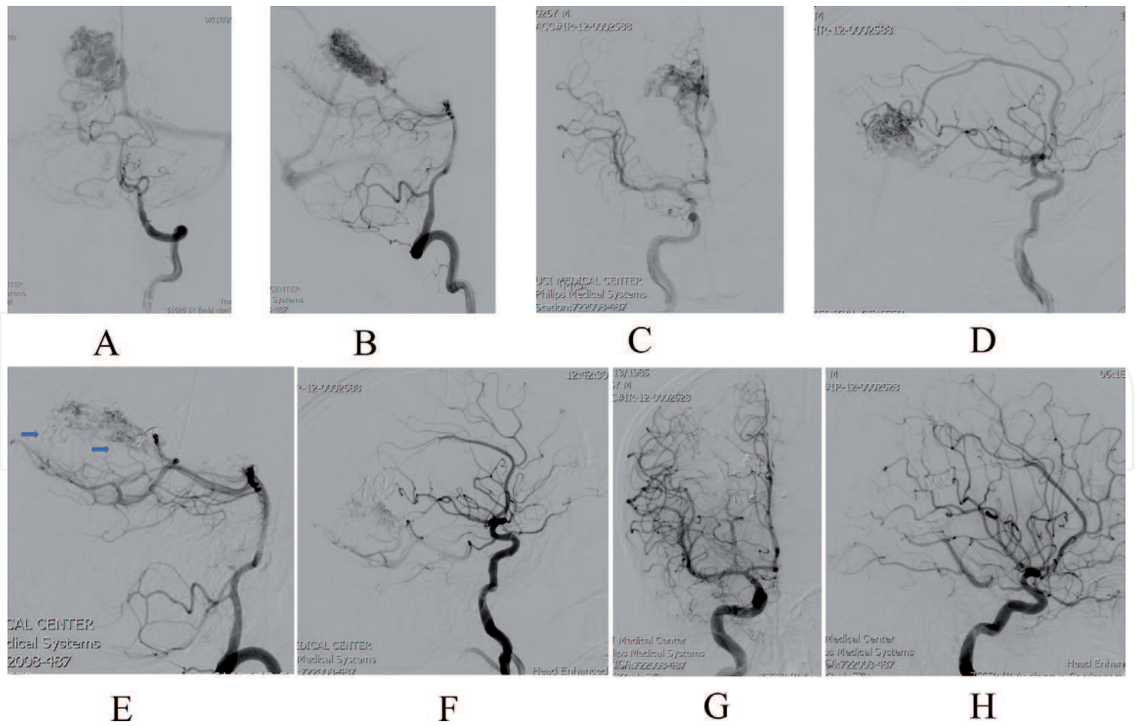

Figure 1.
(A–D) A ruptured choroidal AVM that caused intraventricular and subarachnoid hemorrhage in a 26-year-old male. AVM is supplied by the right posterior cerebral artery (PCA), parietooccipital branch, medial and lateral posterior choroidal arteries, and right pericallosal artery from anterior cerebral artery (ACA). (E and F) Residual AVM supplied by en passage arterial feeders (arrows) from the posterior choroidal arteries and more than 90% size reduction after embolization. These en passage feeders were not amenable to embolization and patient went to surgery for AVM resection on the following day after embolization. Control angiogram after surgical resection does not demonstrate any evidence of a residual AVM (G and H).

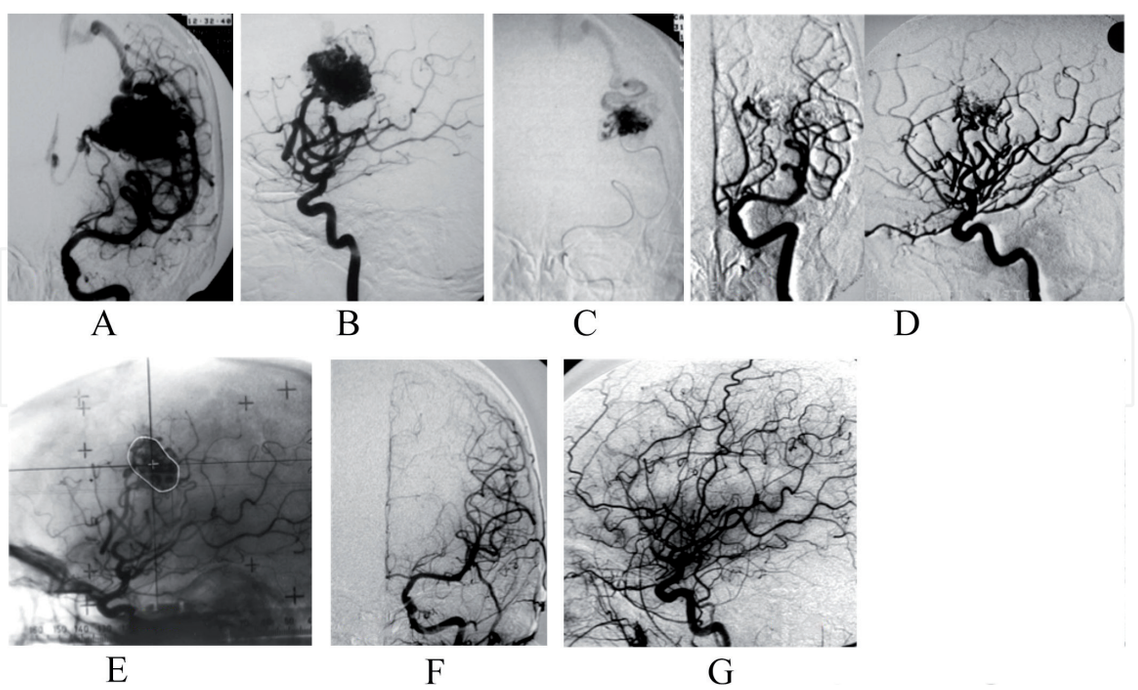

Figure 2.
(A and B) An unruptured left perirolandic AVM supplied by middle cerebral artery branches in a 46-year-old female with headaches. (C) Superselective catheterization and angiogram during preradiosurgical embolization. Postembolization angiograms (D) show at least 90% size reduction with a small residual lesion in the Rolandic region. Stereotactic surgery is planned (E) following embolization due to eloquent location. Follow-up angiograms 2 years after radiosurgery (F and G) demonstrate complete obliteration of the AVM without any residual or recurrent lesion.

There are conflictive reports in the literature regarding the efficiency of embolization before radiosurgery. Whereas some studies have recently mentioned decreased obliteration rates after embolization [27, 28], other studies have demonstrated increased efficacy of radiosurgery with better obliteration rates after embolization [29].

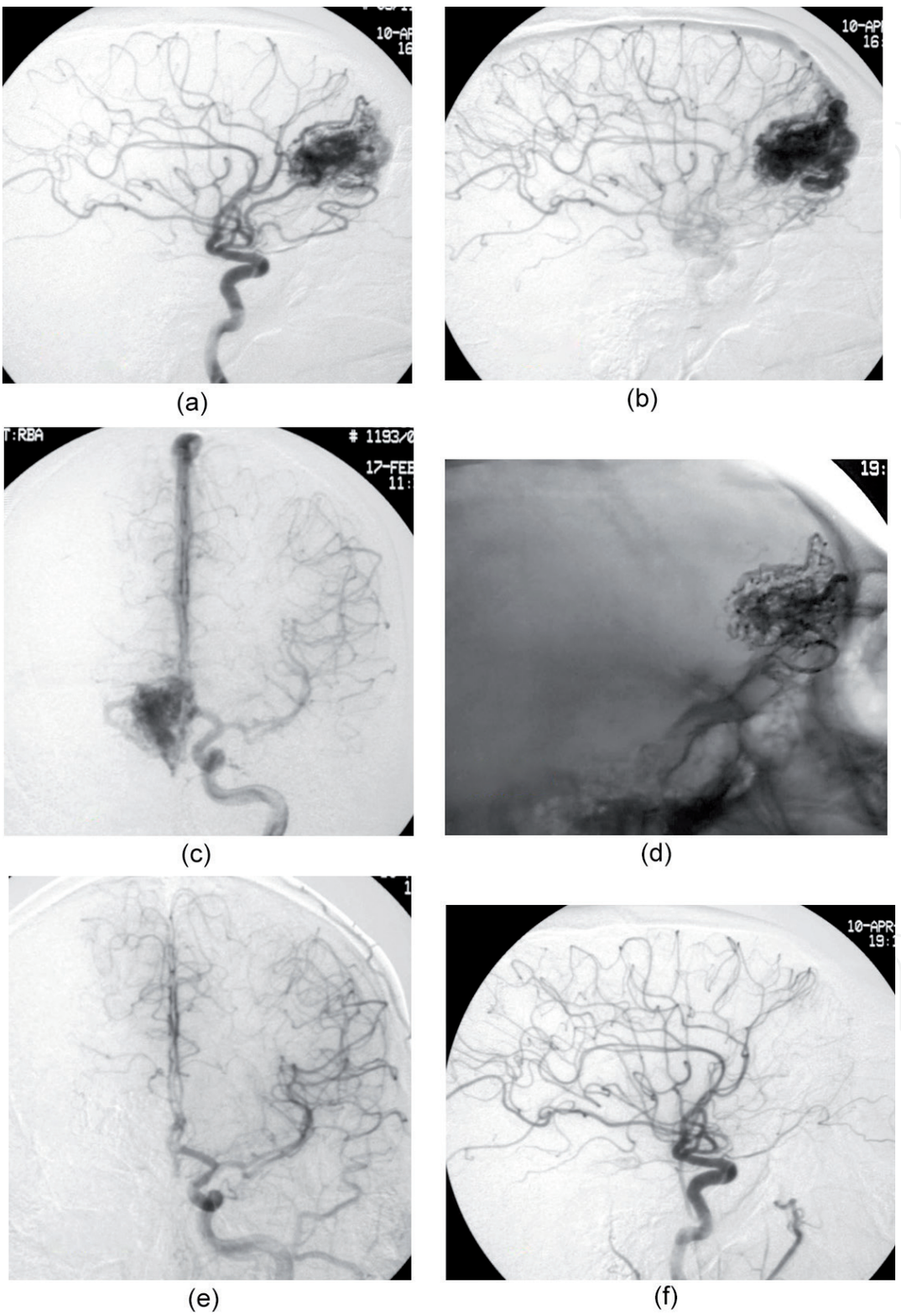

Figure 3.
(A–C) An unruptured frontopolar AVM supplied by the orbitofrontal and frontopolar branches of the right ACA and drained by a single frontal cortical vein into the superior sagittal sinus. (D) The ETOH cast after embolization of two feeders in the same session with a curative intent. ETOH cast completely matches with the angioarchitecture of the AVM. Final angiograms (E and F) show complete obliteration of the AVM without any residual filling.

In our practice, we recommend embolization before radiosurgery for cases with a volume larger than 10 cc, fistulous arteriovenous shunting, and intranidal aneurysms.

2.3 Curative embolization

Complete obliteration rates with embolization have been reported between 9.7 and 14% with NBCA (N-butyl cyanoacrylate) [30]. During the Onyx era, complete obliteration rates with stand-alone embolization rose up to 18–51% [31]. Even higher cure rates up to 94% has been reported in smaller series with selective cases [32]. There were higher rates in AVMs with smaller size and a smaller number of arterial feeders (**Figure 3**). AVMs that have less prominent angiogenic nidus and predominantly fistulous AVMs compared to pure plexiform lesions were also more prone to complete obliteration. Small AVMs with single or less than two feeders with deep and central location are good candidates for stand-alone endovascular treatment. Larger size of the feeding artery also increases the chance of complete angiographic obliteration [33]. According to Valavanis and Yasargil, sulcal AVMs fed by pial arteries are more amenable to safe and effective embolization [34]. Most recent meta-analysis by Wu et al. [31] found an overall complication rate of

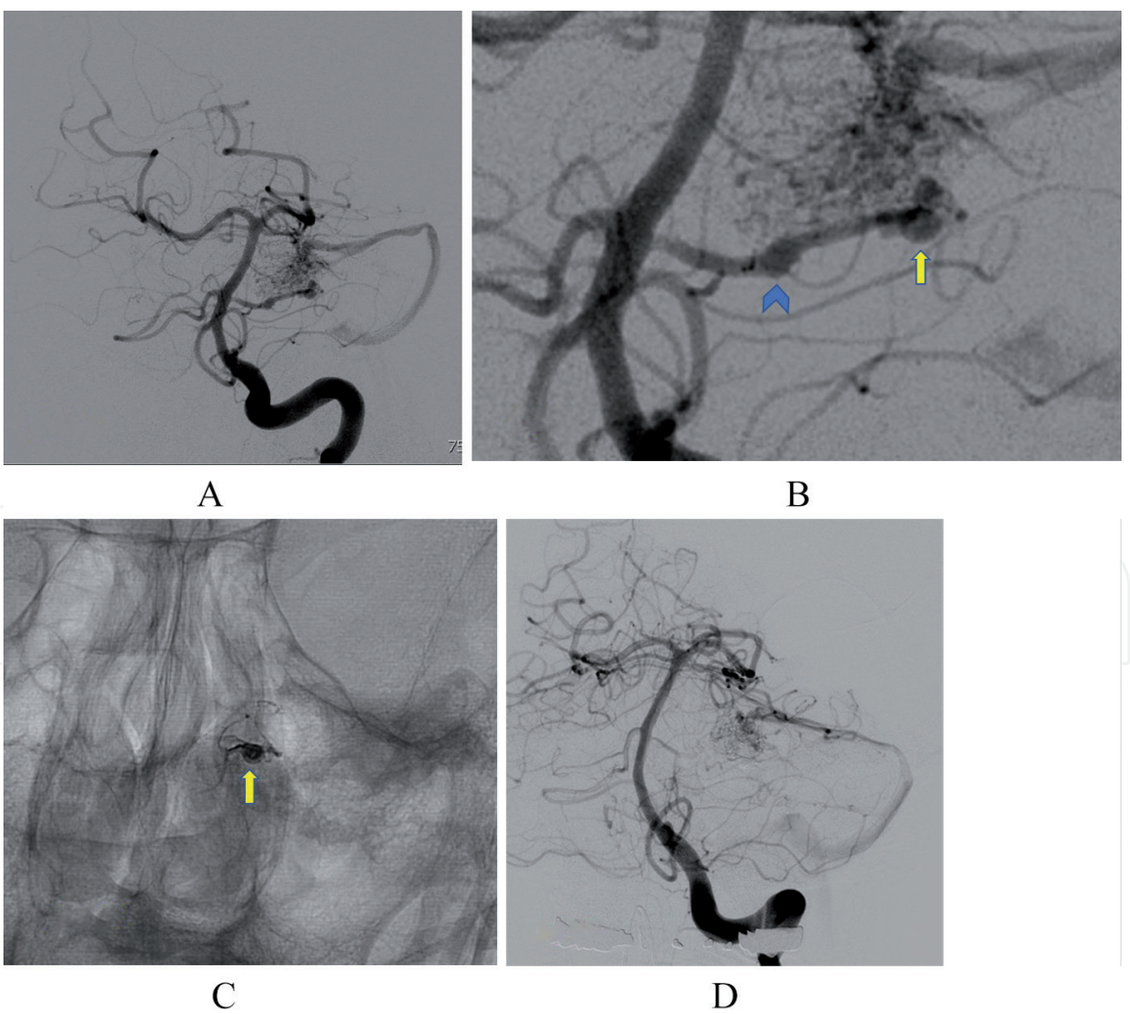

Figure 4.
(A) Ruptured cerebellar AVM supplied by the left anterior inferior cerebellar artery (AICA) branches and with drainage into the left transverse sinus. (B) A flow-related aneurysm on the left AICA and multiple intranidal aneurysms. Unsubtracted angiogram (C) after targeted embolization of the left AICA shows NBCA cast within the aneurysm that was most likely the culprit for the previous rupture and hemorrhage. Postembolization angiogram before surgery (D) shows occlusion of multiple aneurysms with residual AVM.

24.1% including hemorrhage occurring in 9.7% of patients and procedure-related mortality rate of 1.5%. These rates are slightly higher compared with studies where the goal was adjunctive embolization before surgery or stereotactic radiotherapy. Even though stand-alone embolization with intent to cure has the potential to be a safe and efficient treatment, it must be preserved for select AVM cases or can be welcomed as an unanticipated result of an adjunctive endovascular treatment.

2.4 Targeted embolization

Intranidal aneurysm that may cause recurrent bleeding is the main target for embolization if a complete or near complete obliteration is not feasible (**Figure 4**). Aneurysms are more frequently seen in AVMs located in the frontal and occipital lobes. Deep arterial feeders not accessible by surgery are also a good target for embolization. Obliteration of the fistulous component of an AVM and decreasing AVM size by embolization may improve the cure rates after radiosurgery.

2.5 Palliative embolization

Although there is significant debate on the management of unruptured arteriovenous malformations, intractable seizures or intractable headaches may dictate further treatment rather than medical management. Embolization can decrease the severity of these symptoms by theoretically reducing the steal phenomenon and venous hypertension [35, 36]. Embolization of the meningeal supply can relieve intractable headaches. Resolution of trigeminal neuralgia after embolization has been reported [37]. One must always consider risk-benefit balance when considering embolization for symptom relief because partial treatment of large AVMs by embolization or surgery may increase the risk of intracranial hemorrhage [27]. On the other hand, Meisel et al. [38] found that partially embolized AVMs have a lower risk of hemorrhage than the risk expected during the natural course of an untreated AVM.

3. Endovascular technique

3.1 Embolization procedure

Operator needs to know the goal of the endovascular treatment whether it is aiming a complete obliteration, presurgical grade reduction, size reduction before radiosurgery, or a targeted treatment to obliterate weak angioarchitectural points like flow-related aneurysms or intranidal aneurysm causing recurrent hemorrhage. Accordingly, with the specific aims, a game plan can be organized.

In most of the institutions, AVM embolization is performed under general anesthesia. Although some centers advocate conscious sedation over general anesthesia, we do not find it practical to perform embolization in awake patients considering potentially lengthy procedures and absolute need for immobilization during embolysate injection. Triaxial systems with intermediate distal access catheters provide the advantage of much needed stability and momentum in distal and tortuous arterial feeders. A distal access catheter can be navigated to the level of the supraclinoid internal carotid artery, basilar artery, and even in the middle cerebral artery M1 or posterior cerebral artery P1 segments to have a better support.

If the aim is cure or significant size reduction, the ideal position of the microcatheter will be as distal as possible and close to the nidus of the AVM. One must be very careful during microcatheter navigation within the arterial feeders that are prone to dissection or perforation. The safest navigation technique is pushing the

leading microcatheter with a microwire inside and without microwire coming off. Microwire can lead the microcatheter if there is a kink or tortuosity preventing the microcatheter to move forward alone. As soon as the kink or tortuosity is overcome, microwire is withdrawn inside. Navigation technique is different for flow-dependent microcatheters like Magic microcatheter (Balt, Montmorency, France). These microcatheters can be pushed with injection of saline and contrast mixtures and gentle pushing. One must pay attention to avoid kinking of these microcatheters because of poor visibility of the microcatheter shaft that tends to fold on itself when there is too much forward momentum. Gentle superselective microcatheter injections demonstrate the component supplied by the pedicle, venous drainage, and speed of shunting. If there is normal parenchymal blush from the same pedicle, another pedicle is chosen to prevent nontargeted embolization. En passage feeders are challenging because it can be difficult to choose them selectively, and distance to the normal main branch is usually very short for a safe injection. Microcatheter is flushed with saline after contrast injection and before introducing the D5 for NBCA or DMSO for ETOH. The working angle with the longest and straightest view of the microcatheter avoiding overlapping of the nidus and microcatheter must be chosen for the superselective angiogram and liquid embolic injection.

Ideal liquid embolic injection aims to penetrate into the nidus, completely obliterate the nidus, and reach to the very proximal portion of the venous outflow (**Figure 5**). This can be challenging in AVMs with multiple feeders and single draining vein. If the venous outflow is occluded with remaining arterial feeders and a

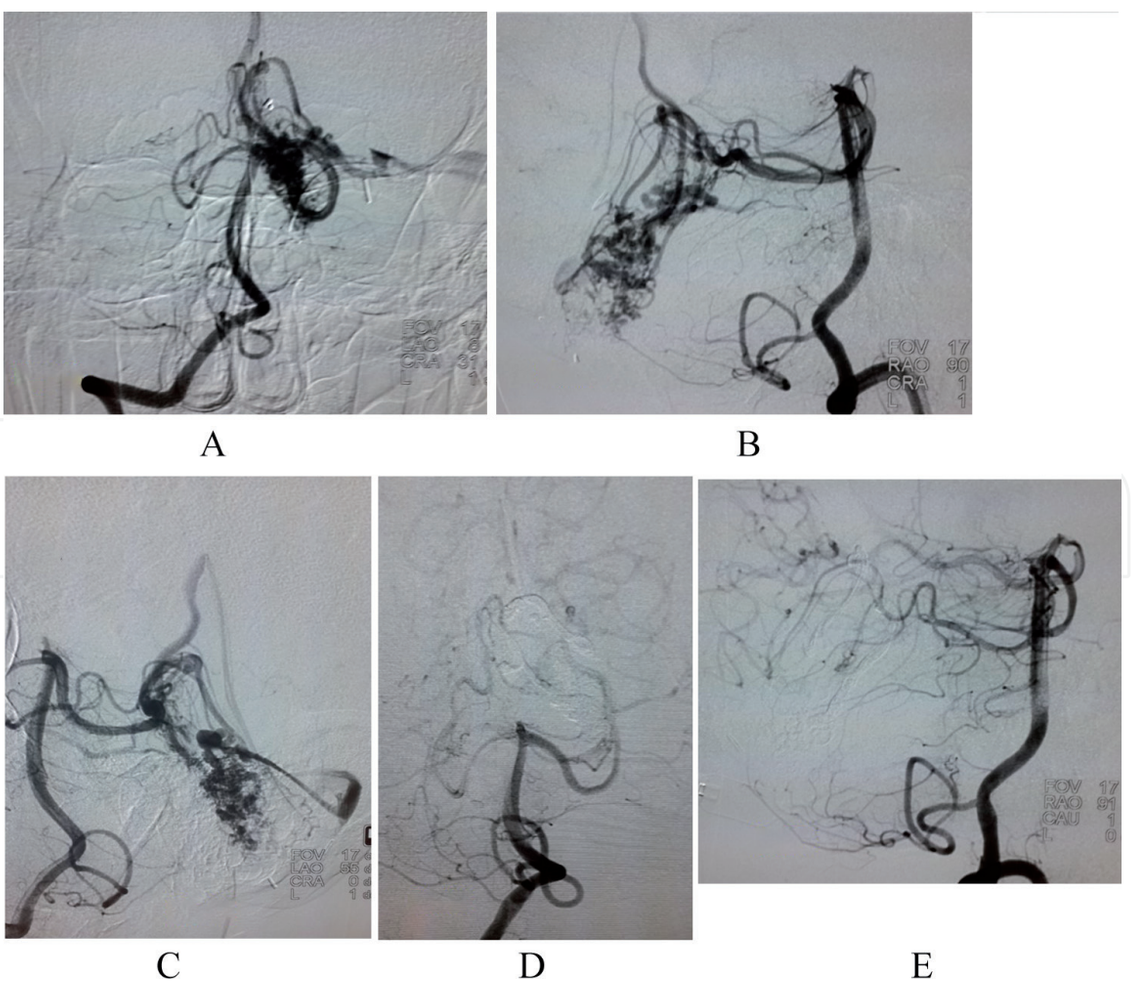

Figure 5.
(A–C) A previously ruptured cerebellar AVM in a 57-year-old-male with prior history of surgery for hematoma evacuation and partial resection of the AVM. (D and E) Complete obliteration of the AVM after embolization.

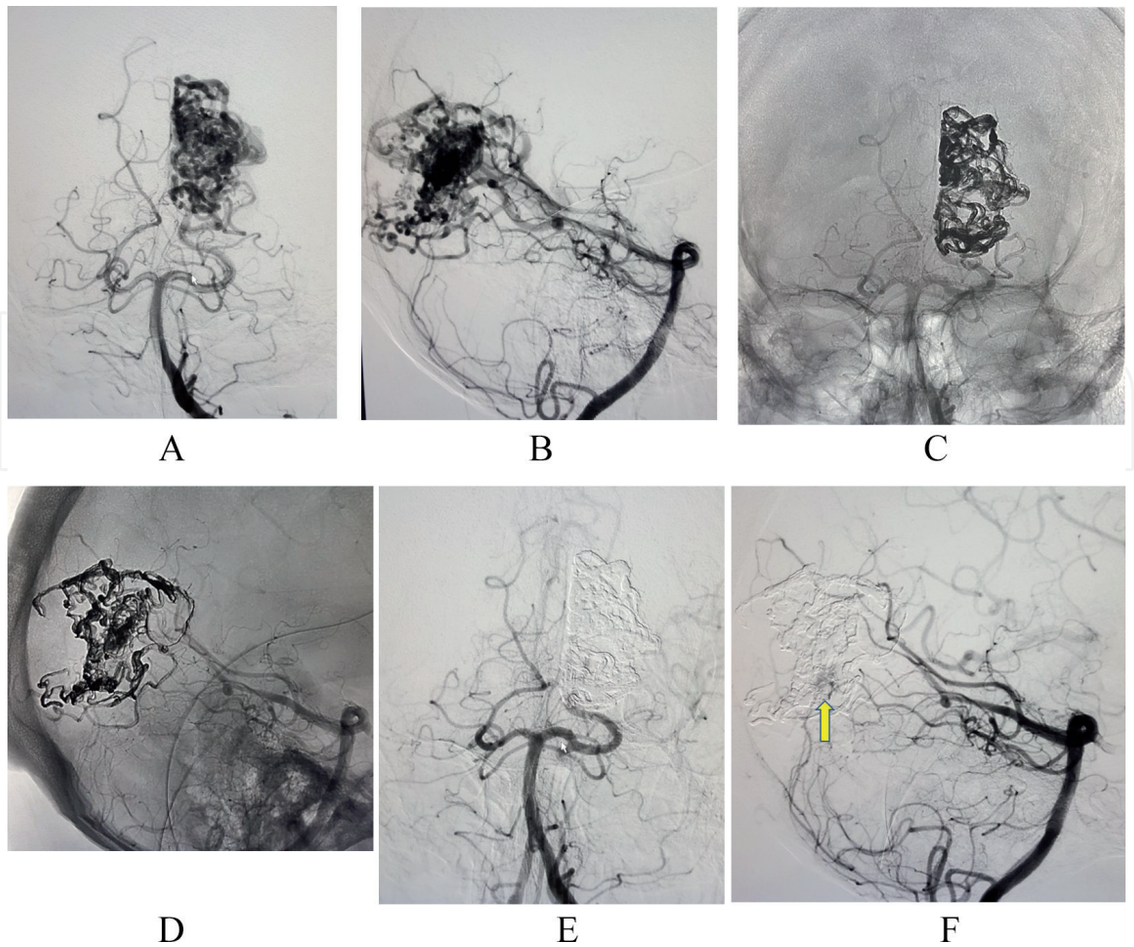

Figure 6.
(A and B) An unruptured posterior fossa AVM. Final angiogram (C and D) after balloon microcatheter-assisted embolization shows the onyx cast almost entirely matching with the AVM. (E and F) A tiny residual filling (arrow) without obvious early venous filling. Patient had surgery following embolization for complete resection of the AVM.

large residual nidal component, a normal pressure breakthrough may occur leading to intracranial hemorrhage. Early venous stagnation with a residual persistent AVM can be an ominous sign and may require complete endovascular obliteration of the AVM if possible or immediate surgical resection (**Figure 6**).

Depending on the angioarchitectural characteristics and preferences and experience of the operator, EVOH or NBCA can be chosen. Although ETOH is used more frequently with the advantages of longer injection times or possibility of halting injections with intermittent angiographic control, NBCA is still preferred by some institutions [39]. Loh and Duckwiler [40] did not find significant differences between two agents in their capacity for at least 50% volume reduction, complication rates, and intraoperative blood loss. NBCA works through polymerization and requires meticulous preparation in order to prevent contamination with blood or saline that may cause premature polymerization. NBCA is prepared in a separate table or in an isolated part of the main table [40]. Operators change their gloves before preparation to prevent contamination and contact of blood with embolic agents. Microcatheter is flushed with D5 before NBCA injection. NBCA mixture can be tailored depending on the arteriovenous shunting. Most common mixture ratios of NBCA to Ethiodol are 1:3 or 1:2 (NBCA:Ethiodol). Denser mixtures can be used if there is a fistulous component with fast flow into the veins. More diluted mixtures can penetrate better into the nidus with the drawback of higher chance of reflux. Another technique to improve the NBCA penetration into the lesion is flushing the guiding catheter continuously with D5 dextrose solution while injecting the glue [41]. Penetration of the NCBA can be

stopped by stopping the D5 perfusion. NBCA is an adhesive agent and microcatheter must be removed briskly as soon as the reflux begins. In both NBCA and ETOH injections, microcatheter is removed while applying negative pressure by gentle aspiration.

ETOH (Onyx, Medtronic, Irvine, CA, USA or Squid, Emboflu, Gland, Switzerland) is a nonadhesive liquid embolic agent, which does not polymerize but precipitates when dissolved with dimethyl sulfoxide (DMSO). ETOH laminates along the venous wall without immediate occlusion of the vessel. Most frequently used ETOH-based liquid embolic agent is Onyx (Medtronic, Irvine, CA, USA). Dead space of the microcatheter is filled with the exact amount of DMSO before ETOH injection. Before injection, we usually mark the screen with a pen showing the landmarks including the most proximal tolerable reflux point on the microcatheter, boundaries of the AVM, and beginning of the venous drainage. Under blank roadmap, ETOH is injected slowly and reflux is watched. In the most popular "plug and push technique," reflux forms a plug of ETOH at the tip of the microcatheter. Some institutions prefer the denser version of ETOH like Onyx 34 (Medtronic, Irvine, CA, USA) to form a plug. After the precipitation of ETOH forming a plug, antegrade penetration into the nidus with new injections is expected. Whenever there is further reflux, penetration into another arterial branch, or early venous penetration, injection is stopped for approximately 90 s. Halting injection for more than 2 min may cause clogging of the microcatheter. If there is no ETOH coming off the microcatheter tip or appearing under blank roadmap 60–90 s after starting injection, injection must be stopped and microcatheter is removed. Clogging of the microcatheter can result in rupture of the microcatheter shaft and extravasation of ETOH [42]. Intermittent angiograms can be done to control the obliteration of the AVM and the status of venous drainage while halting ETOH injections. After a satisfying obliteration is achieved, microcatheter is removed from the system. In ETOH cases, microcatheter is removed by applying constant gentle tension on the microcatheter. If there is a stubborn microcatheter stuck in the ETOH cast, patience with repetitive pulling with constant tension will remove the microcatheter in most of the cases.

Advances in microcatheter technology, development of detachable tip microcatheters, ETOH compatible dual lumen microballoon catheters, and evolution of liquid embolic agents have changed the paradigms in the endovascular treatment.

3.2 New trends in embolization techniques

3.2.1 Balloon-assisted embolization

DMSO compatible balloon microcatheters with double lumen (Scepter, Microvention Terumo, Aliso Viejo, CA, USA and Eclipse, Balt, Montmorency, France) allow injection of ETOH or NBCA while balloon is inflated within the feeding artery [43, 44]. This creates a wedge positioning of the microcatheter like situation or forms a transient plug to increase the penetration of liquid embolic with minimal or no reflux. This will theoretically decrease the fluoroscopy time and radiation dose and increase the ease of microcatheter removal after injection. This technique is especially effective in fistulous AVMs with large caliber feeders. Balloon inflation prevents reflux and allows a more controlled injection in flow arrest conditions. Special attention must be paid during inflation in order to prevent rupture of the feeder. If there is a problem with balloon inflation, uninflated balloon should be replaced as it may increase the chance of catheter entrapment [45]. If there is reflux along the inflated balloon, further gentle inflation usually prevents reflux. Extreme caution must be paid during inflation of the balloon within the arterial feeders to prevent overinflation and rupture.

3.2.2 Transvenous embolization

Although this technique recalls the venous outflow occlusion, one of the most fearful situations for a neuroendovascular specialist during AVM embolization, there is increasing use of transvenous embolization in selective cases [45–47]. Deeply located hemorrhagic AVMs with small tortuous feeders or en passage feeders may have complex anatomy precluding the use of transarterial embolization. Transvenous embolization have theoretical advantages of better penetration of the AVM nidus, less risk of ischemic events due to arterial occlusion, and relatively easier navigation through enlarged and usually straighter veins. Significantly high complete obliteration rates between 80 and 100% [47, 48] were reported in the literature. A transjugular venous access with a triaxial system including a sturdy guiding system of an 8F sheath and distal access catheter is crucial for safe and efficient practice of transvenous embolization. Alternatively, a 6F transjugular access with a 6F distal access catheter can be used. Detachable tip microcatheters or balloon microcatheters in feasible anatomy may prevent reflux and occlusion of the venous drainage. Some centers intentionally let an approximately 3 cm reflux after a longer injection and leave the microcatheter inside the system after cutting the microcatheter shaft at the skin incision site. Mendes et al. [47] did not report any thromboembolism associated with transvenous embolization cases with transjugular access where all microcatheters were left intentionally within the venous system. Arterial access and arterial flow arrest with transient balloon occlusion or simultaneous transarterial embolization should be used if technically feasible. Although there is no established standard practice of transvenous embolization, theoretical criteria to select cases include small lesions with a nidus of <2 cm, hemorrhagic AVMs, patients who are not good surgical candidates, arterial feeders that are not amenable to transarterial embolization like en passage feeders, lenticulostriate arteries or choroidal arteries, and AVMs preferably with a single drainage vein [46, 48]. Nonadhesive ETOH should be used for transvenous embolization [49]. Systemic hypotension during and after transvenous embolization is also crucial for decreasing the arterial pressure that must be overcome for better nidal penetration. Another technical challenge for transvenous embolization arises from frequently encountered venous anatomical variations and fragile structure of the cerebral veins that may lead to disastrous consequences in case of vessel injury. One must pay extreme caution for safe transvenous navigation of the microcatheter without leading microwire. Aneurysms, ectasia, or stenosis in the draining vein may preclude transvenous embolization due to high risk of vessel injury during navigation.

3.2.3 Pressure cooker technique

Pressure cooker technique (PCT), first described by Chapot et al. [50], applies a plug composed of coils and glue instead of the usual ETOH plug used in the regular plug and push technique. Coils are deployed and NBCA is injected to form a plug. A microcatheter for ETOH injection is placed in the optimal position in the feeding artery followed by a second microcatheter placed in between the tip of the first microcatheter and detachment zone. As described by the sheeping technique, placement of the first microcatheter usually facilitates the navigation of the second security microcatheter [32, 51]. A 1.2F Magic (Balt, Montmorency, France) microcatheter is used in small caliber vessels and Echelon 10 (Medtronic, Irvine, CA, USA) is used as a second microcatheter in relatively larger caliber arterial feeders. Since detachable coils are not compatible with Magic 1.2F microcatheter, injectable flow coils (SPIF, Balt, Montmorency, France) are used. In case of larger caliber

vessels with high flow arteriovenous shunts, injectable coils may flow unintentionally toward the tip of the first microcatheter. Detachable coils are deployed through a regular 1.7F like Echelon 10 (Medtronic, Irvine, CA, USA) for precise placement of the coil and glue plug. This type of plug is more resistant to ETOH reflux and facilitates a more forceful and continuous ETOH injection. It creates a wedge-like position similar to ETOH injection through the balloon microcatheters. The theoretical advantages compared to balloon-assisted embolization are better navigability of flow-directed microcatheters and avoidance of risk of vessel perforation during balloon inflation.

4. Complications of the endovascular treatment

Overall morbidity and mortality rates from the largest series of AVM embolization range from 0 to 22% and 0 to 3%, respectively [52–56]. Intracranial hemorrhage during or after the embolization can be seen in between 2 and 4.7%. Most common reason for hemorrhage is vessel perforation due to microcatheter or microwire manipulations. Venous outflow obstruction and normal perfusion pressure breakthrough are other mechanisms that may cause bleeding after embolization. Normal perfusion pressure breakthrough is believed to occur due to overdilated capillaries in the parenchyma surrounding the AVM in the setting of steal phenomenon or ischemia. After embolization or resection of the AVM, increased pressure or perfusion in the surrounding parenchyma may cause rupture of the maximally dilated capillaries [57]. Staged embolization is preferred in large AVMs in order to prevent normal perfusion breakthrough phenomenon [58]. If the surgical resection is not planned to immediately follow the embolization, a staged embolization in several sessions is performed. Although there is no established rule, less than 50% size reduction is aimed in every session in order to prevent postembolization hemorrhage. About 4–6 weeks can be waited in between every session for hemodynamic stabilization. If there is significant slowing of the venous drainage during any moment of embolization, either complete obliteration must be achieved by embolization or surgical resection must be performed urgently following embolization. Therefore, it is utmost important to evaluate the venous drainage pattern before and immediately after the embolization. In rare cases, perforation and bleeding may occur during superselective microcatheter injection in a small branch. If there is any concern for intraoperative rupture or postprocedural neurological deterioration happens, a brain computerized tomography must be obtained to rule out hemorrhage. In case of hematoma with mass effect or impending expansion risk, emergent craniotomy for hematoma evacuation helps minimize neurological deficit and may avoid mortal consequences [59].

Ischemic complications can occur due to thromboembolism from the embolic material or thrombus formation within or along the guiding catheter or microcatheter. Mechanisms or thromboembolism are reflux or nontargeted flow of the liquid embolic into a normal branch during embolization. Heparinization is routinely used during AVM embolizations. Other general complications related to angiographic procedure include groin hematoma, retroperitoneal hematoma, arteriovenous fistula, and contrast nephropathy with similar frequencies compared to other neurointerventional procedures.

Buffalo grading system [60] is used to stratify the risks associated with endovascular treatment with curative intent. Risk of the endovascular treatment increases with number of arterial feeders, smaller diameter of the feeders, and eloquent location. One point is given for AVMs with one or two arterial feeders, 2 points is given

for three or four arterial feeders, and 3 points is assigned for four or more pedicles. If the diameter of the most feeders is less than 1 mm or AVM is in an eloquent location, an additional point is given. Starke et al. [61] proposed another scale to predict various factors increasing complication risk in AVM embolizations. This scale is very similar to Spetzler-Martin grading system for surgical morbidity-mortality and includes same factors including size (1 point for <3 cm and 2 points for >6 cm), eloquent location, and deep venous drainage. They proposed the need for more than one session of embolization as an additional risk factor with increased complication rate. However, Crowley et al. [56] did not find any significant difference in the complication and morbidity/mortality rates depending on the Spetzler-Martin grades. The same study did neither show a significant difference in complication rates between the ETOH versus NBCA cases.

Microcatheter retention may occur between 3 and 8% of cases [42]. Risk of microcatheter retention increases after longer injections with long reflux, in smaller branches and branches with significant curves and tortuosity. If the vessel accommodating the microcatheter has tortuosity, long refluxes must be avoided. Safe reflux for an efficient push and plug technique is usually between 15 and 20 mm. Smaller vessels with or without tortuosity require a smaller reflux of less than 10 mm [50]. Although ETOH is nonadhesive and initially microcatheter retention was expected to decrease with ETOH use, clinical practice and experience demonstrated the contrary. The risk increased due to longer injection times and the need for a significant reflux to form a plug for efficient ETOH injection. Loh and Duckwiler [40] found higher incidence of microcatheter retention and difficulty in removing the delivery microcatheter in the first trial comparing Onyx to NBCA, which led to FDA approval of the Onyx. ETOH is less thrombogenic than NBCA and does not cause immediate occlusion in case of an unintended flux.

Development of detachable tip microcatheters including Apollo (Medtronic, Irvine, CA, USA) and Sonic (Balt, Montmorency, France) has substantially decreased the incidences of microcatheter retention [62]. These microcatheters have variable lengths (1.5 or 3 cm) of detachable tip segment that allows better estimate of tolerable reflux thanks to markers, and detachment will occur if there is enough reflux to create a tension point. Sonic (Balt, Montmorency, France) microcatheter usually detaches after a long injection with substantial reflux; whereas Apollo (Ev3) microcatheter may not detach in many cases and can be retrieved as a whole without detachment.

Introduction of distal access catheters helped better navigation of very distal tortuous feeders and facilitated retrieval of microcatheters after a long injection. The use of distal access catheters is almost the standard of practice especially for cases with superficial lesions with distal and tortuous feeders. Distal location of a guide catheter eliminates the need for repeated navigation of a microcatheter through a tortuous supraclinoid internal carotid, anterior, middle cerebral artery, or basilar artery.

Although recanalization after complete obliteration of an AVM is extremely rare, there is still risk of recanalization that mandates angiographic follow-up after complete obliteration. Potts et al. [63] in their extensive review of multiple series of AVMs cured with embolization found 4.5% recurrence rate on follow-up angiography. However, there was not any case of recurrence with rupture or any adverse event during follow-up period. Mechanisms that may lead to recurrence include incomplete embolization due to nonvisualization of a component during initial embolization, mass effect from a hematoma, or recanalization of an initially thrombosed compartment.

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