13 Angiographic Intervention in Hemorrhagic Stroke

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13.1 General Principles

13.1.1 Overview

Angiographic intervention has an important role in the diagnosis and treatment of hemorrhagic stroke. In terms of diagnostic tools, conventional cerebral angiography remains the gold standard for the diagnosis of ruptured vascular lesions, such as intracranial aneurysms, arteriovenous malformations (AVMs), and dural arteriovenous fistulas (dAVF). In addition, for intracerebral hematomas in young patients or those without identifiable risk factors, conventional cerebral angiography should also be performed to exclude the possibility of occult vascular lesions. Furthermore, substantial advancements in endovascular surgery are accelerated by various factors, including rapid advances in imaging technology, continued medical device development, and technical improvements. As a result, the competence of angiographic intervention in the management of hemorrhagic stroke has progressed from an alternative to surgery for inaccessible intracranial lesions or inoperable patients to frontline treatment tools. Previously inaccessible neurovascular lesions have become treatable with these minimally invasive techniques, with reduced morbidity and mortality using the angiographic intervention.

The most notable field in angiographic intervention is the treatment of intracranial aneurysms. Surgical treatment of intracranial aneurysms can, in most cases, achieve complete elimination of the aneurysm without compromising the parent vessel or adjacent perforators. However, several risk factors might increase the risk of morbidity and mortality. These factors include the aneurysm size, morphology, and location. The age, neurological status, and medical comorbidities of the patient also play a role. According to the International Subarachnoid Aneurysm Trial (ISAT), patients with subarachnoid hemorrhage fare better with coil embolization than with surgical clipping [1]. More recently, the Barrow Ruptured Aneurysm Trial also showed better outcomes of coil embolization compared with those of surgical clippings [2]. In recent decades, endovascular coiling was also limited by the aneurysm morphology and adjacent vascular structure, and the introduction of balloon- or stent-assisted techniques reduced the area of the “uncoilable” aneurysm. More recently, a new generation of endovascular devices – the flow diverter – became available. Wide-necked large, giant, and blood-blister aneurysms are treated with the flow diverter by mechanisms of

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flow redirection and neoendothelialization across the aneurysmal neck [3–5].

In the field of AVM and dAVF, endovascular surgery can be used individually or as part of multimodal treatments with stereotactic radiosurgery and surgical resection. While surgical resection remains the most definite treatment option, embolization can achieve total AVM occlusion in selected AVM patients with deep located small-sized AVMs [6]. In addition, for carotid-cavernous fistula and other forms of dAVF, endovascular surgery is a good treatment option. Several embolic materials are available, including n-butyl cyanoacrylate, polyvinyl alcohol, and Onyx, which are appropriate embolic materials that can be used in individual cases.

13.1.2 Preoperative Evaluation

The operators should identify the patient's general and neurological status. A review of the medical records, including medical comorbidities (hypertension, diabetes mellitus, cardiac disease, chronic kidney disease, and allergic history), history of antiplatelet and anticoagulant medications, and previous computed tomography (CT) and magnetic resonance image (MRI), is necessary. Laboratory evaluation including kidney function (BUN/creatinine) is essential. If impaired renal function is identified, the use of nonionic contrast agents, procedural hydration, and pretreatment with sodium bicarbonate or oral N-acetylcysteine should be considered. The operator should also be in a position to recognize and manage acute hydrocephalus and intracranial hypertension.

13.1.3 Preparation for Endovascular Surgery

During the perioperative period of hemorrhagic stroke, an emergent situation can often be encountered. To control blood pressure, inotropic agents (dopamine or phenylephrine) or antihypertensive agents should be prepared. Anticoagulant status is critically important for successful endovascular surgery, with systemic heparinization needed. Likewise, protamine sulfate for rapid reversal of the heparin effect also should be prepared in case of intraprocedural rupture. If an adjuvant procedure (balloon or stent-assisted techniques) is expected, 300 mg of clopidogrel can be administered, with intravenous aspirin considered on a case-by-case manner.

13.1.4 Anesthesia and Monitoring

Most endovascular surgeries are performed under general anesthesia. In some circumstances, such as a high risk of general anesthesia, conscious sedation may be acceptable. An arterial line is placed in the radial artery to closely monitor the patient's blood pressure, and anesthesiologist is aware of the need to avoid blood pressure fluctuation. Arterial oxygen saturation and cardiac rhythm are monitored during the procedure. For the early detection of neurological deterioration, neuro-monitoring such as somatosensory-evoked potential (SSEP) and motor-evoked potential (MEP) can be prepared.

13.1.5 Conventional Cerebral Angiography (Fig. 13.1)

All endovascular surgery should be performed in the angiography suite with biplane digital subtraction and fluoroscopic imaging capabilities. Many vascular neurosurgical diseases that were previously treated as high risk in the operating room can now be safely treated in the angiography suite. However, prior to endovascular surgery of hemorrhagic stroke, satisfactory cerebral angiography should be performed.

Conventional cerebral angiography is critical to determine the optimal treatment for hemorrhagic stroke. For planned coil embolization of ruptured intracranial aneurysm, three-dimensional rotational reconstructive image is necessary to accurately assess the aneurysm morphology and location, including its size, geometry, dome to neck ratio, and relationship to

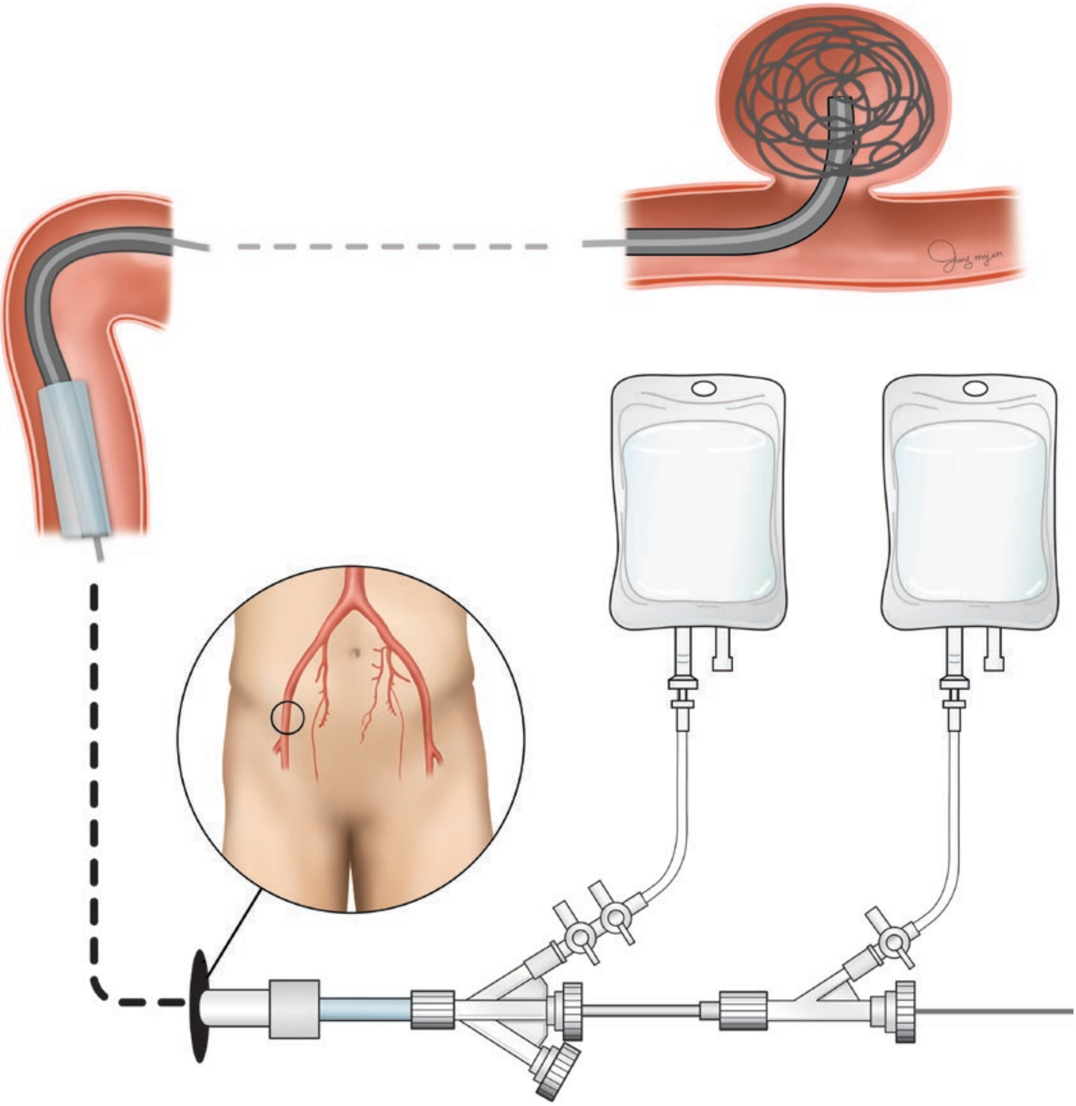

Fig. 13.1 A schematic representation of the coil embolization system

the parent vessel and involved arterial branches, so that working views can be planned appropriately. Furthermore, for the treatment of AVM or dAVF, conventional cerebral angiography can also provide highly detailed information regarding the anatomic features in all phases, including points of fistulous connections, associated aneurysms, nidus size, and arterial and venous flow patterns necessary for utilizing the Spetzler-Martin grading scale, but they can also provide important hemodynamic information regarding dominant arterial filling and pedicle arrangements. Therefore, preoperative conventional cerebral angiography should be of sufficient quality to characterize vascular lesions. In the case of large and giant aneurysms, AVM, and dAVF, it is essential to evaluate both external carotid arteries.

Furthermore, the operator makes the overall technical decision based on the angiographic details. Selection of the diameter and system of guiding catheter, angle and number of microcatheters, and planned adjuvant technique (balloon or stent assist) are planned carefully.

Ultimately, if endovascular surgery is planned, an immediate preoperative angiography is necessary to evaluate the vascular anatomy and to ensure the appropriateness of the planned procedure.

13.1.6 Intraprocedural Management

The operator should be aware and prepared to acutely manage intraprocedural complications, such as thromboembolic complications, intraprocedural aneurysm rupture, misplaced or herniated embolic materials, flow-limiting vasospasm, arterial dissection, and arterial rupture.

If intraprocedural complications are detected, a detailed review of angiographic image and immediate management should be performed. Pretreatment angiographic images of the lesions, parent vascular tree, and capillary blush are mandatory to evaluate intraprocedural complications. Emergency cross-sectional imaging must be available if a procedure-related complication occurs or is suspected.

A thromboembolic event is major complication of endovascular surgery, so systemic heparinization is necessary. With any endovascular surgery, it is crucial to employ proper anticoagulation to minimize the risk of thromboembolic complications, but heparin may not be administered for hemorrhagic stroke, especially in the situation of aneurysmal SAH due to risk of rebleeding. Systemic heparin is usually withheld until at least the framing coil has been deployed into the ruptured aneurysm [7]. A continuous catheter flushing system is also important for prevention of flow stasis and thromboembolism. A commonly used system for continuous flushing is the Tuohy-Borst Y-valve setup, which provides a constant stream of heparinized flush (3000–6000 units per liter) using a pressurized bag at rate of 150–200 mL minimum per hour. The operator should check the patient's anticoagulant status and maintenance of the flushing system.

Intraprocedural aneurysm rupture and arterial perforation during endovascular surgery have continued to be devastating complications. If such complications occur, immediate management should be performed, including rapid heparin reversal, use of a temporary occlusion balloon to tamponade the bleeding site, and rapid aneurysm occlusion. In the case of massive intracranial hematoma or acute hydrocephalus, emergency computed tomographic imaging should be used to identify the problem, and emergent ventriculostomy may be performed in a case-by-case manner [8].

13.2 Principles of Angiographic Intervention in SAH

13.2.1 Brief Concept of Coil Embolization in the Acute Phase of SAH

In the acute phase of SAH, urgent treatment of ruptured aneurysms is recommended because of the high risk of rebleeding associated with a poor prognosis. Therefore, therapeutic occlusion of the ruptured aneurysm is one of the most important treatment goals of SAH [9]. Endovascular techniques offer the prospect of reducing the risk of rebleeding without the need for craniotomy [10]. The ruptured aneurysm is packed with various coils that block the circulating blood flow from the parent arteries and induce thrombosis.

Endovascular techniques are classified into reconstructive and deconstructive treatments according to the occlusion of parent artery. Reconstructive endovascular techniques include simple coil embolization, balloon-assisted coil embolization, stent-assisted coil embolization, and flow diversion. These techniques reduce the risk of rebleeding by blocking the aneurysm from the circulating blood flow without occlusion of the parent artery. Deconstructive endovascular technique is used to occlude the parent artery containing the aneurysm and is a viable and durable solution for certain intracranial aneurysms. In particular, it has been used for the treatment of aneurysm involving the vertebrobasilar junction and posterior cerebral artery when adequate collateral flow is present.

13.2.2 Simple Coil Embolization

Since Dr. Guglielmi first introduced electrolytically detachable platinum microcoils in 1990, the coil embolization technique has been continuously developed with advancements of endovascular devices. Simple coil embolization is the mainstream technique in endovascular treatment. Under fluoroscopic guidance, various catheter systems are navigated from the arterial circulation entrance to the parent artery containing the ruptured aneurysm. A microcatheter is placed in the aneurysm and progressively filled with various types of detachable coils that are suitable for the shape of the aneurysm. The aneurysm cavity is first filled with a framing coil. Additional coils of various sizes, shapes, and softness are filled until a sufficient packing density is obtained. The filled coils isolate the aneurysm from the circulating blood flow, and the remaining space is filled with a thrombus (Fig. 13.2a–d). It is well known that packing the coils as tightly as possible is important to avoid recanalization. However, excessive coil packing may result in intraprocedural ruptures, and appropriate packing is required. It is controversial, but a packing density (coil volume/aneurysm volume × 100%) of 20–25% has been reported to be effective for avoiding recanalization [11]. Simple coil embolization is feasible for aneurysms that have narrow neck or favorable dome to neck ratio (generally defined as a neck less than 4 mm in diameter or a dome to neck ratio greater than 2) (Fig. 13.3), to hold the coils within the aneurysm cavity.

The multiple catheter technique (Fig. 13.4a) is a method for treating aneurysms with an unfavorable anatomy using two or more catheters. Neck remodeling techniques, such as the balloon- or stent-assisted technique, are widely used to treat aneurysms with a less favorable anatomy. However, there are some technical difficulties in performing these techniques. The introduction of additional devices into small intracranial vessels may increase the risk of vascular injury, and these

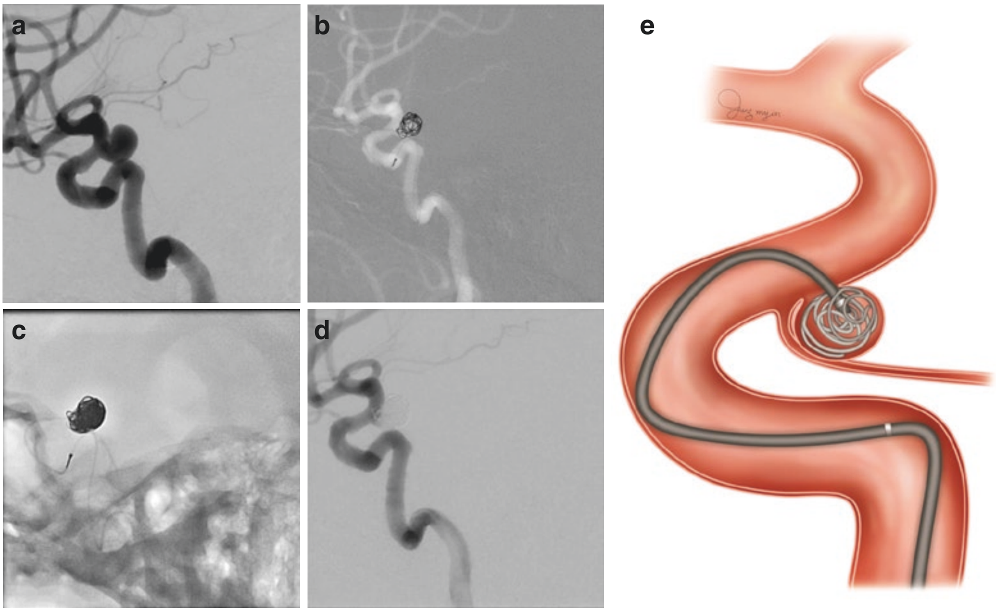

Fig. 13.2 Simple coil embolization technique. Case. Simple coil embolization technique for the posterior communicating artery (PcomA) aneurysm. (**a**) Initial digital subtraction angiography (DSA) shows an aneurysm arising from the origin of PcomA. (**b**) The frame coil and subsequent coils were deployed through a microcatheter located in the aneurysm cavity. (**c**) Complete occlusion of the aneurysm was achieved. (**d**) Post-procedural DSA shows the treatment result. (**e**) An illustration of simple coil embolization. The frame coil is deployed through a microcatheter located in the aneurysm cavity

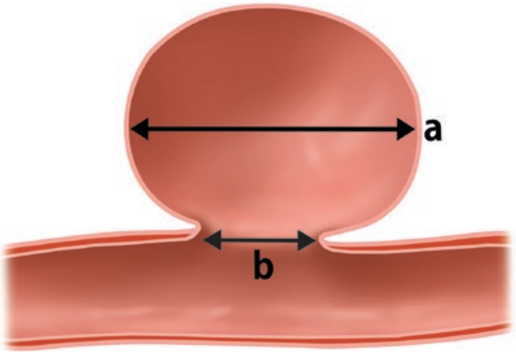

Fig. 13.3 A schematic representation of the dome to neck ratio (a/b). An aneurysm with a less favorable anatomy is usually defined as having a neck larger than 4 mm or a dome to neck ratio of 2 or less

neck remodeling techniques may be unsuitable for use in aneurysms, such as those with important branches arising from the fundus [12]. Baxter et al. described a double microcatheter technique for the detachable coil treatment of large, wide-necked intracranial aneurysms in 1998. In this technique, the initial coil frame is stabilized with two coils by interlocking them with each, and it is based on the concept of securely bracing the coils adjacent to one another to achieve a stable configuration [12, 13]. The multiple catheter technique might be helpful when there is evidence of coil instability or parent vessel compromise during embolization of an aneurysm with a wide neck or unfavorable dome to neck ratio [13].

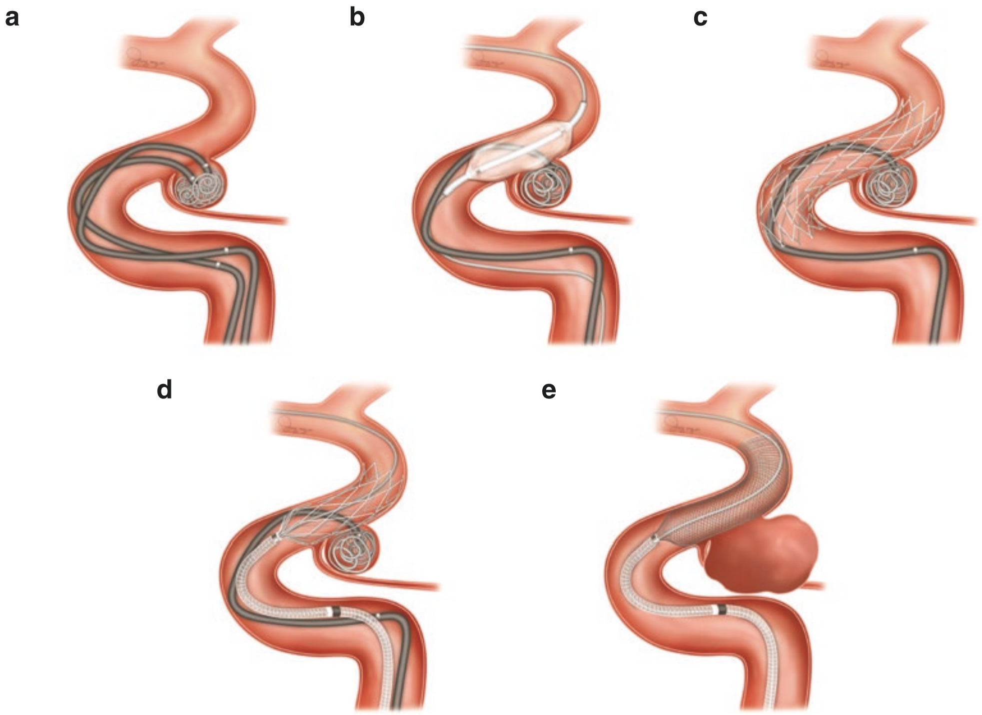

Fig. 13.4 (**a**) Multiple catheter coil embolization technique. Two microcatheters are located in the aneurysm cavity. The frame coils from each microcatheters interlock with each other, stabilizing the initial coil frame. (**b**) Balloon-assisted coil embolization technique. The balloon is located across the aneurysm neck and serves as a temporary supportive scaffold. (**c**) Stent-assisted coil embolization technique. The stent is placed across the aneurysm neck. The stent provides a permanent supportive scaffold for stabilization of the coil mass. (**d**) A schematic representation of stent-assisted coil embolization use by the jailing technique. Aneurismal catheterization is performed before deployment of a self-expandable stent across the aneurysm neck. Thus, the microcatheter is "jailing" between the stent and the parent vessel wall. (**e**) A schematic representation of the flow diversion device across the aneurysm neck

13.2.3 Balloon-Assisted Coil Embolization

In the case of aneurysms with a wide neck or unfavorable dome to neck ratio, simple coil embolization may jeopardize the patency of the parent artery because the filled coils cannot be stabilized in the aneurysm cavity. Moret et al. first described balloon-assisted coil embolization in 1997, a technique that provides temporary supportive scaffolding to the neck of these aneurysms by inflation of a compliant microballoon (Fig. 13.4b) [14]. It prevents the coils from protruding into the parent artery and leads to higher packing densities and more effective parent vessel reconstruction [15]. Balloon-assisted coil embolization has gained popularity for the treatment of ruptured aneurysms with a less favorable anatomy (wide neck or unfavorable dome to neck ratio) because it does not require the routine use of antiplatelet agents [16]. Moreover, balloon inflation allows control of the extravasation and prevents devastating consequences for the patient [17]. The stent-assisted technique does not provide side branch protection from coil herniation or proximal control during an intraprocedural rupture. Thus, when a side branch is in close proximity to the neck of an aneurysm, the balloon-assisted technique can be an effective and safe modality.

However, there are some concerns about the potential morbidity associated with this technique, especially the high risk of thromboembolic complications [18] related to the use of two microcatheters and hemodynamic stasis due to balloon inflation [17]. Sluzewski et al. reported that compared with simple coil embolization, balloon-assisted coil embolization techniques were associated with higher thromboembolic complications and intraprocedural rupture [19]. Several studies have suggested that the balloon-assisted technique should be reserved for cases in which the conventional coil embolization technique is inappropriate, but there is no consensus concerning this issue.

13.2.4 Stent-Assisted Coil Embolization

Endovascular strategies for managing aneurysms with a less favorable anatomy, such as a wide neck and unfavorable dome to neck ratio, have previously included the balloon remodeling technique [20]. However, many aneurysms still cannot be guaranteed based on the technical feasibility and the long-term durability of the balloon remodeling technique. Unlike the balloon-assisted technique, stent-assisted coil embolization provides permanent supportive scaffolding via the deployment of an intracranial stent for stabilization of the coil mass (Fig. 13.4c). This procedure reduces the rate of aneurysm recanalization by redirecting the blood flow reducing the intra-aneurysmal flow and promoting endothelialization at the level of the aneurysm neck [21–24].

In the early days of the stent-assisted technique, the stents for coronary and peripheral vascular embolization were experimentally applied to the cerebral vessel. However, the characteristics of balloon-expandable coronary stents have limited their use in cerebral aneurysm therapy. They lack sufficient flexibility such that excessive force during deployment could damage the vessel wall [20]. The ideal stent for cerebral vessels should have a low profile, be flexible, and consist of self-expandable material to accommodate the complex geometry of the intracranial arteries [20]. Since the first US Food and Drug Administration (FDA) approval of the Neuroform stent (Stryker Inc.) in 2002, a variety of stents have been developed and applied.

There are two types of stents depending on their design: open-cell (in which not all struts are interrelated) and closed-cell (in which all stent struts are interconnected). The aforementioned Neuroform stent is an open-cell designed stent with relatively fewer thromboembolic complications in the form of procedure-related transient ischemic attack (TIA) and stroke [25]. In contrast, the Enterprise stent (Codman Inc.) is the first closed-cell designed stent to treat intracranial aneurysms, and the advantages of the closed-cell stent include the ability of the stent to be partially deployed, recaptured, and redeployed [21, 25]. It is also easier to deploy than the open-cell stent and enables the treatment of additional aneurysms, but the closed-cell design of the stent has a greater tendency to slightly alter the normal vascular anatomy owing to its design [21, 26].

When performing stent-assisted coil embolization, aneurismal catheterization is performed before deployment of a self-expandable stent across the aneurysm neck (Jailing technique) (Fig. 13.4d). Following deployment of the stent, embolization coils are delivered with the microcatheter positioned within the aneurysm dome and wedged between the stent and the aneurysm dome [27]. This technique prevents the situation in which a stent is deployed but the aneurysm cannot be subsequently catheterized [28]. In particular cases, such as dissection of the aneurysm or basilar top aneurysm, the stent-assisted technique may be applied as an overlapping or Y-stenting technique.

There is reluctance to deploy stents in the setting of SAH because of the risk of thromboembolic complications in patients who are not prepared with antiplatelet agents, and fear of the use of antiplatelet agents during the acute phase of SAH may increase the risk of rebleeding. There is no clear consensus about the use of antiplatelet agents, but in several recent studies, a proper antiplatelet therapy regimen did not increase intracerebral hemorrhage during the acute phase of SAH treated with stent-assisted coil embolization [16].

13.2.5 Flow Diversion Devices

Flow diversion is the placement of a low-porosity, high-pore-density device in the parent vessel at the aneurysm neck to decrease flow into the aneurysm and redirect the flow to the distal part of the parent vessel [29]. The lower the porosity, the better are the chances of occluding the aneurysm, but excessive low porosity would lead to occlusion of any branch covered by the device. Most flow diversion devices have a porosity of approximately 70%, whereas conventional intracranial stents have a porosity of approximately 90%. The pore density is the number of metal-enclosed pores per unit surface area [30]. A higher pore density can increase the uniform coverage across the aneurysm neck and potentially limit the perforator occlusion. A lower porosity and increased pore density are design goals for flow diversion devices aimed at occluding aneurysms.

Accordingly, flow diversion devices promote endothelialization of the flow diversion device and subsequently block the aneurysm from the circulating blood flow over time, while there is no occlusion of the covered adjacent branches (Fig. 13.4e). The main hemodynamic effects that lead to aneurysm thrombosis without the placement of intra-aneurysmal material are the decrease in velocity of intra-aneurysmal flow, reduction in flow turbulence, and reduction of wall shear stress [31, 32]. After the Pipeline for Uncoilable or Failed Aneurysm Study (PUFS) was completed, the Pipeline embolization device (Medtronic) was first approved for use by the US FDA in 2011.

The use of flow diversion devices without adequate antiplatelet therapy can be associated with serious thrombotic complications such as in-stent thrombosis and thromboembolism. Current flow diverters necessitate 3 months of dual antiplatelet agents and lifelong aspirin to avoid in-stent thrombosis [29]. However, the use of antiplatelet agents in the acute phase of SAH is controversial due to potential bleeding complications. In addition, compared with conventional coil embolization or surgical clipping, flow diversion does not achieve immediate aneurysm obliteration and does not decrease the risk of immediate rebleeding. Thus, flow diversion after aneurysmal SAH is not preferred as the primary therapeutic option. Natarajan et al. recommended that flow diversion is not the primary treatment of choice after aneurysmal SAH, but it is a reasonable final option if other, safer options are not available to treat the aneurysm [29].

13.2.6 Limitation

Since the ISAT, endovascular coil embolization has become a favorable therapeutic option for patients with SAH. However, there are questions about the durability and long-term efficacy of coil embolization. Aneurysm remnants or recurrences and the need for retreatment are more common after endovascular coiling than after clipping. Therefore, follow-up imaging is mandatory.

13.3 Other Indications Including Dural AV Fistula and AVM

Intracranial dural AV fistula and AVM are abnormal arteriovenous channels without a capillary bed. The difference between AV fistula and AVM is the presence or not of a nidus. Both diseases present with intracerebral hemorrhage.

In dural AV fistula, leptomeningeal reflux is related to venous hypertension and will be a predisposing factor for intracerebral hemorrhage. The goal of endovascular treatment obliterates abnormal fistulous channels without interfering with normal venous drains. Endovascular treatment can be accessed via the transvenous, trans-arterial route or direct puncture of the affected dural sinus. Advances have been achieved in embolic material and devices for trans-arterial endovascular treatment rather than transvenous endovascular treatment. Endovascular treatment is a primary treatment for dural AVF presenting with intracerebral hemorrhage (Fig. 13.5a).

In AVM, combined dural AVF and prenidal, intranidal, or flow-related aneurysms are predisposing factors for AVM rupture. Endovascular treatment has not been a primary treatment modality for ruptured AVM because low complete angiographic obliteration rate in endovascular treatment will increase rebleeding of the ruptured AVM. In general, endovascular treatment is performed before microsurgical resection to enhance the surgical accessibility. In ruptured small AVM that are not feasible for surgical resection, endovascular treatment demonstrated a high complete angiographic obliteration rate and will be considered a primary treatment option (Fig. 13.5b).

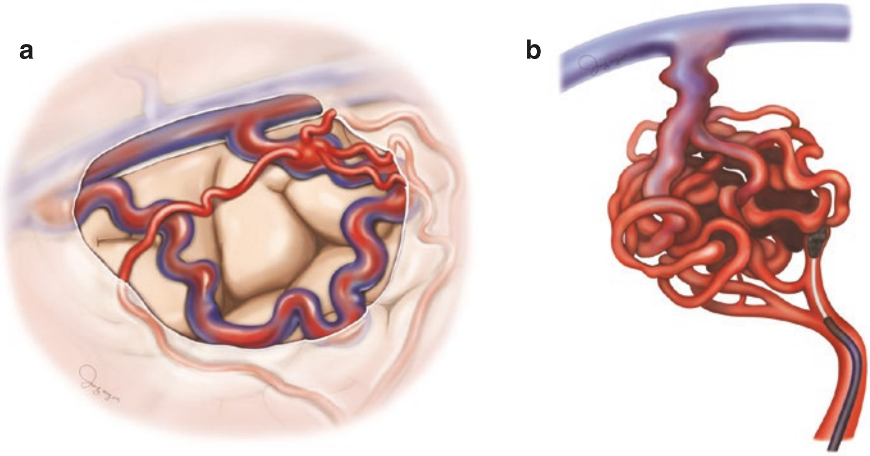

Fig. 13.5 (**a**) A schematic representation of the dural arteriovenous fistula (dAVF). This figure shows the connection between the meningeal arteries and cortical vein. There is retrograde blood flow into the superior sagittal sinus and the engorged cortical vein. (**b**) A schematic representation of the arteriovenous malformation (AVM). The microcatheter is placed in one feeding artery, and Onyx is allowed to occlude the proximal parts of the draining veins and nidus

13.3.1 Endovascular Treatment for Dural Arteriovenous Fistula

13.3.1.1 Definition of Dural Arteriovenous Fistula and Classifications

A dural arteriovenous fistula is defined as an abnormal arteriovenous malformation without a nidus between dural arteries and adjacent venous sinuses with occasional reflux into the cortical veins [33]. They represent 10–15% of all cerebral vascular malformations [34]. dAVF have been classified as a benign type with a dural sinus drain or an aggressive type with a leptomeningeal drain and/or reflux, which may be associated with hemorrhage or nonhemorrhagic neurologic deficits [35]. The classification systems defined by Cognard et al. [36] and Borden et al. [37], which are designed to grade the risks and natural course of dAVF, have been widely used.

13.3.1.2 Target of Endovascular Treatment of Ruptured dAVF

With the advancement of embolic materials and devices in the field of neurointervention, endovascular treatment is now regarded as the primary treatment option, especially in high-risk dAVF such as hemorrhagic presentation. The primary objective of endovascular treatment is to obliterate occlusion of the entire fistulous channels with preservation of normal venous channels. However, in complex dAVF with an expectation to avoid obliteration of total fistulous channels, the goal of endovascular treatment is an intentional partial treatment strategy with reversal of the aggressive type of dAVF to a benign type to facilitate subsequent Gamma Knife radiosurgery or neurosurgery [38, 39].

13.3.1.3 Endovascular Access Routes

Conventionally, transvenous endovascular treatment that occludes fistulous channels and the adjacent affected sinus has been widely used. However, transvenous endovascular treatment is not always possible for the isolated affected sinus or stenotic dural sinus. With the development of liquid embolic materials such as Onyx or PHIL, trans-arterial endovascular treatments that occlude feeding arteries and fistulous channels have been attempted and gradually increased. In cases of small-calibered, tortuous feeding arteries, trans-arterial endovascular treatment may be challenging. Additionally, embolization of feeding arteries that are at risk for anastomosis in the internal carotid or vertebral artery may cause cerebral/cerebellar infarction or cranial nerve palsy. In dAVF that are challenging or inaccessible via trans-arterial or transvenous access, direct puncture of the affected sinus via transorbital or craniotomy has provided good results [40–42].

13.3.1.4 Embolic Materials

Embolic materials are classified into detachable fibered/non-fibered coils, particles (polyvinyl alcohol, PVA), and liquid embolic materials. The liquid embolic materials that are currently used include n-butyl-2-cyanoacrylate (NBCA; Codman, Raynham, MA, USA), Onyx (eV3; Neurovascular Inc., Irvine, CA, USA), and PHIL (MicroVention-Terumo; Tustin, CA, USA). Coils are mainly used for transverse occlusion of the affected sinus. PVA is not a durable treatment option, and it has not been recently applied. It was previously used for benign dAVF as a palliative treatment or for residual fistulous channels as an alternative treatment. NBCA named “glue” is a cheap, fast embolic material, and it was widely used to occlude dAVF trans-arterially before the advent of Onyx or PHIL [43]. Because NBCA is a liquid adhesive, its major disadvantages are a short injection time, insufficient glue casting of fistulous channels, unexpected gluing of normal drain veins, and a low cure rate (30–50%) [44, 45]. Because Onyx is a cohesive liquid embolic agent, it provides a slow and controlled injection unlike NBCA, resulting in a larger amount of Onyx cast into the fistulous channels, which is related to a higher angiographic cure rate [46, 47]. PHIL is another cohesive liquid embolic material composed of hydroxyethyl methacrylate (PHEMA) and dimethyl sulfoxide. Accordingly, PHIL also provides a slow and controlled injection. Additionally, computed CT or MRA after PHIL embolization showed fewer artifacts and good delineation of the embolic cast due to the absence of a metal component such as tantalum.

Endovascular treatment using PHIL showed a similar angiographic cure rate compared with that of Onyx [48].

In conclusion, endovascular treatment of dAVF includes a number of options with varying risks and effectiveness for individual lesions. Endovascular treatment of dAVF is a proven safe and effective method for treating these complex cerebrovascular lesions.

13.3.2 Endovascular Treatment for Arteriovenous Malformation

13.3.2.1 Definition of AVM and Natural History

Arteriovenous malformations (AVMs) are direct connections between arteries and veins without a capillary bed and consist of anomalous entangled vessels defined as a nidus. Approximately 2% of hemorrhagic strokes are caused by AVMs [49]. Hemorrhagic stroke is the most common symptom of AVMs, ranging from 53 to 65% [49, 50]. The annual risk of hemorrhage ranges from 1.3 to 4% per year [49, 51], increasing to 6–7% during the first year after the first hemorrhagic stroke [51, 52]. AVF and prenidal, intranidal, or flow-related aneurysms have been reported to increase the risk of AVM rupture [53, 54]. The morbidity of ruptured AVMs has been reported to be half or two-thirds of ruptured AVMs [55, 56]. Mortality has been reported to be approximately one to two-tenths of ruptured AVMs.

13.3.2.2 Objectives of Endovascular Treatment for Ruptured AVMs

Endovascular treatment of ruptured AVM may have varying goals. The first goal of endovascular treatment is mainly to decrease the arterial supply or the AVM size to resect AVM easily before surgery. By decreasing the AVM size as well as its blood flow, endovascular treatment has been reported to shorten the operation time and reduce blood loss [57]. Endovascular treatment and subsequent microsurgery can treat AVM in a staged manner, resulting in a reduction of blood flow to the nidus that will prevent normal pressure perfusion syndrome such as postoperative hemorrhage [58].

Another goal of endovascular treatment is to reduce the AVM size or to eliminate high-risk features for radiosurgery. Outcomes of combined endovascular treatment and subsequent radiosurgery have shown varying degree of complete occlusion ranging from 14 to 90% [59]. Endovascular treatment before radiosurgery was found to be most effective for AVM with a size of 4–6 cm for which approximately 90% were reduced to a size that was amendable to radiosurgery [60].

For small-sized ruptured AVM positioned in a deep location, endovascular treatment may be the primary treatment option to obliterate AVM angiographically. The selection of patients should be a cardinal rule for endovascular treatment to cure AVMs. Small AVMs with few feeding arteries, a compact rather than a diffuse nidus, and an absence of perinidal angiogenesis are positive factors for curing AVMs primarily by endovascular treatment [61, 62].

For AVMs that are not amenable to treatment, palliative or targeted treatment of high-risk features such as associated aneurysms or fistula is considered. However, partial endovascular treatment is not recommended because the outcome of partial endovascular treatment seems to be worse than the natural history [63, 64].

In conclusion, endovascular treatment of ruptured AVMs may play a pivotal role in obliterating AVM completely for microsurgery or radiosurgery. Endovascular treatment should be carefully considered as a primary treatment option for carefully selected AVMs with a favorable profile for complete AVM obliteration.

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