Chapter

The History and Development of Endovascular Neurosurgery

Xianli Lv

Abstract

Endovasuclar neurosurgery, neuroendovascular surgery and neurointervention are all defined as endovascular diagnosis and treatment of vascular lesions involving the brain and spinal cord using catheters in the DSA (digital subtraction angiography) unite. Based on literature evidences, the field of endovascular neurosurgery has evolved rapidly and successfully over the past half century and has resulted in effective endovascular therapies for carotid-cavernous fistulas (CCFs), intracranial aneurysms, arteriovenous malformations (AVMs), dural arteriovenous fistulas, atherosclerosis of cerebral arteries, acute stroke, carotid artery disease, and vascular tumors of the head, neck, and spinal vascular malformations and tumors. The scope of practice of neurovascular endovascular surgery has become complex, requiring training in specific skill sets and techniques. The evolution of the neuroendovascular field has resulted in the development of program requirements for residency or fellowship education in endovascular neurosurgery.

Keywords: cerebral aneurysm, arteriovenous malformation, stroke, endovascular technique

1. Introduction

Endovascular neurosurgery is now the most commonly practiced therapeutic approach for most vascular lesions involving the brain and spinal cord [1]. At the beginning, balloons are the only available techniques; latter coils, embolic agents, and stents are introduced [2]. With expansion of the endovascular devices and techniques, the treatment strategies for cerebrospinal vascular diseases has been refined [3]. Neurosurgeons must have the mindset to embrace and nurture the progress and technologic advances. The pioneers of endovascular neurosurgery considered the impossible and tenaciously stood by their dreams [4]. Their revolutionary ideas and inventions truly reflected their courage, faith, and determination. The shift away from open surgical approaches has had far-reaching implications for how we train neurosurgical residents and fellows and how we certify these individuals once their training is completed [5]. With the maturity of endovascular neurosurgery technology, we need to re-examine the resident and fellow training for neurovascular surgery. This chapter traces the evolution of endovascular neurosurgery and its current role as the dominant and frequently standard therapy for cerebral and spinal vascular diseases.

2. Cerebral angiography

Endovascular neurosurgery is based on cerebral angiography. It is well known that Portuguese neurologist Antonio Egas Moniz, the recipient of the Nobel Prize in Physiology and Medicine in 1949, developed and described cerebral angiography firstly in 1927 [6]. Before using cadaveric specimens of human to develop the technique, he had successfully obtained cerebral angiograms in dogs. His first cerebral angiography was performed in a 48-year-old patient with Parkinson's disease. The internal carotid artery (ICA) was ligated temporarily for 2 minutes and a 70% solution of strontium bromide was injected into the ICA at a dose of 13 to 14 ml. The middle and posterior cerebral arteries were demonstrated on his first film. Unfortunately, the patient died from thrombophlebitis 8 hours later. This invention ushered in the age of diagnostic and therapeutic angiography.

Cerebral angiography had a prominent role in defining neurosurgery as a specialty distinct from surgery. The cerebral angiography is based on X-ray imaging [7]. Contrast injection plus X-ray exposure combined with mask subtraction generates images of high resolution of the cerebral vasculature. In early angiogram systems, cut film and film cassettes were used, which required a technologist to exchange multiple cassettes to obtain series and angiography "runs". At that time, angiography generated radiopaque images of the cerebral vasculature and could be used to identify vessel occlusions and eventually identify vascular lesions [8]. Distortion and displacement of the vascular anatomy could be used for hematoma or tumor localization.

There has been an ongoing evolution of the cerebral angiography, first as a diagnostic tool but then the potential for intervening in vascular pathology became possible. Subsequently, the eventual introduction of braided catheters and hydrophilic wires, which allowed quick and safe catheterizations, set the foundation for intervention. Modern digital subtraction angiography (DSA) machines consist of an image intensifier and digital subtraction flat panel detectors that utilize a fraction of the radiation dosage for the acquisition of images of the finest detail [9]. The ability to rotate the image intensifier around the patient allowed the development of 3D rotational images [10].

Although cerebral angiography remains a mainstay in the diagnosis and endovascular treatment of cerebrospinal vascular disorders [11], several limitations of this technique are evident. X-ray based cerebral angiography cannot view neurovascular structures clearly in complex vascular lesions, lack resolution necessary to visualize small vessels and critical perforating vessels, which are essential to the treatment of many cerebrovascular disorders. As a real-time guide during therapy, intraluminal imaging with ultrasonography, maybe a resolution in the future. This technique will provide not only therapeutic guidance but also real-time documentation of the completeness of therapy.

3. Cerebral aneurysms

Endovascular treatment of cerebral aneurysms had its start in neurosurgery. Werner et al. firstly reported successful electrothermic thrombosis of an intracranial aneurysm in 1941 [12]. With a transorbital puncture, "thirty feet of No. 34 gauge coin silver enameled wire was introduced into the aneurysm through a special needle" and "the wire was heated to an average temperature of 80°C for a total of 40 seconds. The aneurysm no longer bled when the needle was cleared at the conclusion of the operation" [12].

After these early attempts, particularly in the 1960s and early 1970s, several neurosurgeons and neuroradiologists sought therapeutic alternatives to conventional surgery [2]. Lacking devices suitable for safe navigation in the intracranial vasculature, their efforts originally concentrated on the extravascular route. Under radiographic guidance, thrombosis was initiated by passing electrical current to an electrode needle introduced within the aneurysm sac through a burr hole [13]. Mullan et al. described the treatment of intracranial aneurysms in a series of 12 patients, 10 of whom had presented with aneurysmal subarachnoid hemorrhage, by inducing electrothrombosis [13].

Until 1964, Luessenhop and Velasquez made the first endovascular attempt to treat a cerebral aneurysm [14]. They attempt to occlude a supraclinoid aneurysm with a silicone balloon. Subsequently, Serbinenko developed a balloon-mounted microcatheter with flow-directional capabilities for more effective intracranial catheterization [15]. He further developed detachable and nondetachable balloon catheters to make parent artery sacrifice or direct aneurysmal obliteration and to allow temporary balloon occlusion safe and reliable in the 1970s. His contributions gave birth to endovascular neurosurgery [15]. Balloon occlusion techniques were further used with a vast amount of clinical experience during the 1970s and 1980s [16–18].

Several major limitations of balloon occlusion technique are apparent. Aneurysmal catheterization was difficult without help of guidewire. The balloon shape often could not adequately filling an irregular aneurysm with leaving the fundus unprotected or creating a ball-valve effect of aneurysmal refilling. Therefore, the endovascular therapy of cerebral aneurysms shifted from balloon occlusion to free (pushable) platinum coil occlusion [2]. At this time, coil embolization for cerebral aneurysms is a dangerous procedure because of the inability to retrieve the pushed coils that migrated into the distal intracranial vasculature.

The innovation of electrolytic detachable coils by the Italian neurosurgeon Guido Guglielmi in the early 1990s updated the endovascular treatment of cerebral aneurysms [19, 20]. In the early 1980s, Guglielmi found accidental electrolytic detachment of the electrode tip while applying current to a stainless steel electrode inserted into an experimental aneurysm to promote electrothrombosis. After several years, he worked with Ivan Sepetka, an engineer at Target Therapeutics, Inc., to combine the two processes of endovascular electrolysis and electrothrombosis, which eventually resulted in the development of the present-day Guglielmi detachable coil (GDC; Boston Scientific/Target Therapeutics, Fremont CA) [21]. The Guglielmi detachable coil (GDC) can be re-positioned and examined before the coil was released electrolytically from its tether. On the other hand, the flexibility and softness of the coil enabled the safe filling of an irregular aneurysm with a low risk of rupture. The first intracranial aneurysm was treated using this new technology on April 12, 1990 [19]. The first multicenter GDC clinical trial result was published by Guglielmi et al. in 1992 [20]. Immediate complete occlusion was obtained in 81% of small-necked and 15% of wide-necked aneurysms with low procedure-related morbidity and mortality rates less than 5%. The GDC system was immediately accepted worldwide and became the focus of most published works on cerebral aneurysm management (**Figure 1**).

Despite the advantages of the GDC system, wide-necked and large aneurysms remained difficult to treat. New techniques were performed to keep the detached coils within the aneurysmal sac. Moret et al. was the pioneer of the "remodeling technique" using a balloon as a mechanical barrier to keep coils within the aneurysmal sac during its delivery (**Figure 2**) [22]. Moret et al. [22] published their results with use of the "balloon-remodeling technique" for the treatment of 56 cases of previously untreatable wide-necked cerebral aneurysms in 1997 with low morbidity and mortality rates.

An alternative approach to introduce a stent to maintain a patent lumen and provid a buttress to prevent coil herniation. After some early attempts of Wakhloo

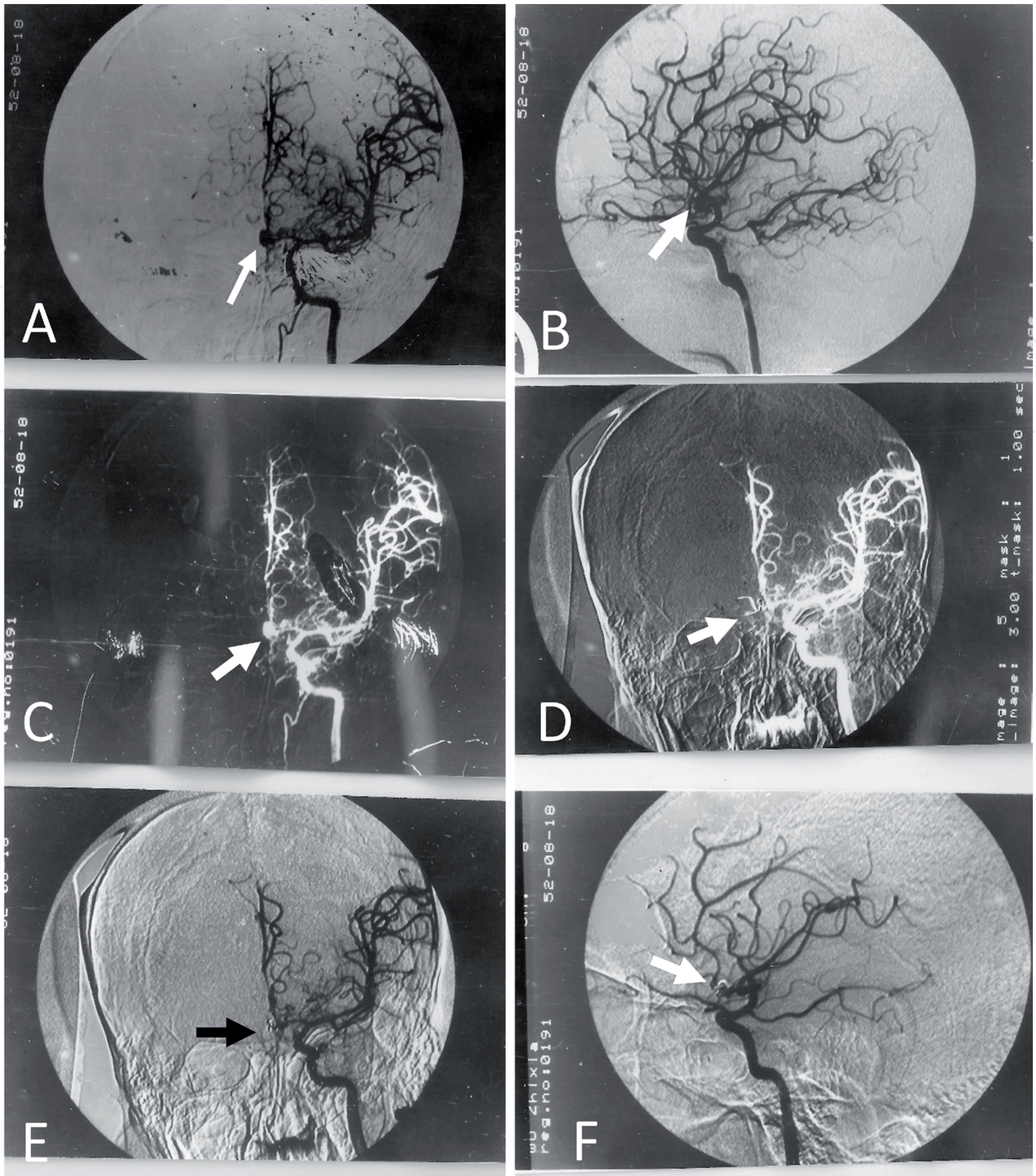


Figure 1.
A 46-year-old woman with a ruptured anterior communicating artery aneurysm was coiled with GDCs (Boston Scientific, USA) in 1998. A, frontal view of the left internal carotid artery injection. B, lateral view of the left internal carotid artery injection. Showing the aneurysm of the left anterior communicating artery (arrows). C, frontal view of the roadmap image of the left internal carotid artery injection showing the aneurysm (arrow). D, frontal view of the roadmap image after aneurysm coiling showing the disappearance of the aneurysm (arrow). E, frontal view of the left internal carotid artery injection after aneurysm coil embolization. F, lateral view of the left internal carotid artery injection after aneurysm coil embolization. Showing the aneurysm was completely occluded (arrows).

et al. [23] and Geremia et al. [24], this stent-assisting technique has been further explored and expanded by an increasing number of neurosurgeons [25]. Neurosurgeons and neurointerventional radiologists at several centers began to borrow stents from the interventional cardiology at the same time and publish their case reports about treating wide-necked aneurysms with a combination of stents and coils (**Figure 3**). These stents were designed specifically for cardiac usage and were stiffer and more difficult to use in the tortuous neurovascular anatomy.

With the introduction of neurovascular stents, specifically designed for intracranial use (Neuroform stent, Boston Scientific Target), borrowing cardiac stents soon became unnecessary [26]. Although the use of stents required a regimen of

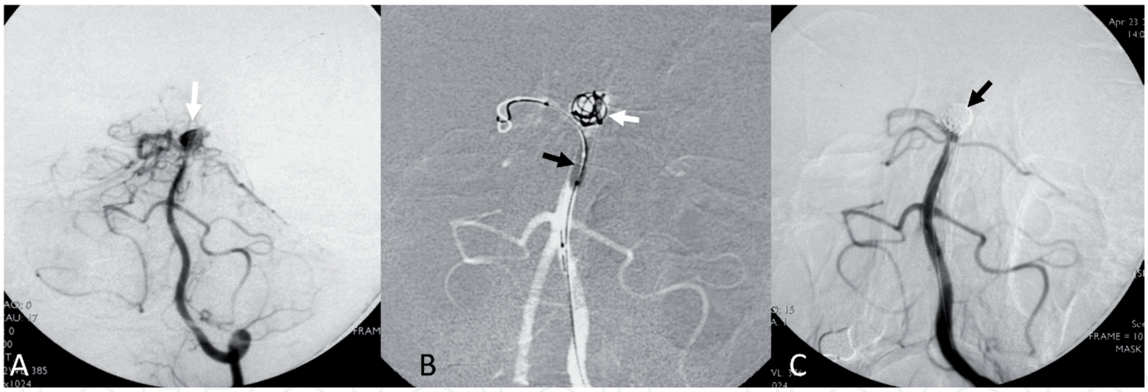


Figure 2.
A 37-year-old man presented with subarachnoid hemorrhage. A, frontal view of the left vertebral artery injection showing a basilar tip aneurysm (arrow). B, roadmap of the left vertebral artery injection showing the first orbit 3-D 7 mm × 13 cm coil and a 4 mm × 20 mm Hyperglide balloon catheter (Medtronic ev3, USA) (arrow). C, the left vertebral artery injection showing the aneurysm was completely occluded after subsequent coils (Microplex 6 mm × 15 cm,6 mm × 10 cm, 5 mm × 10 cm, orbit 5 mm × 15 cm, HydroCiol 3 mm × 7 cm, 2 mm × 4 cm, helix standard fiber 2 mm × 4 cm).

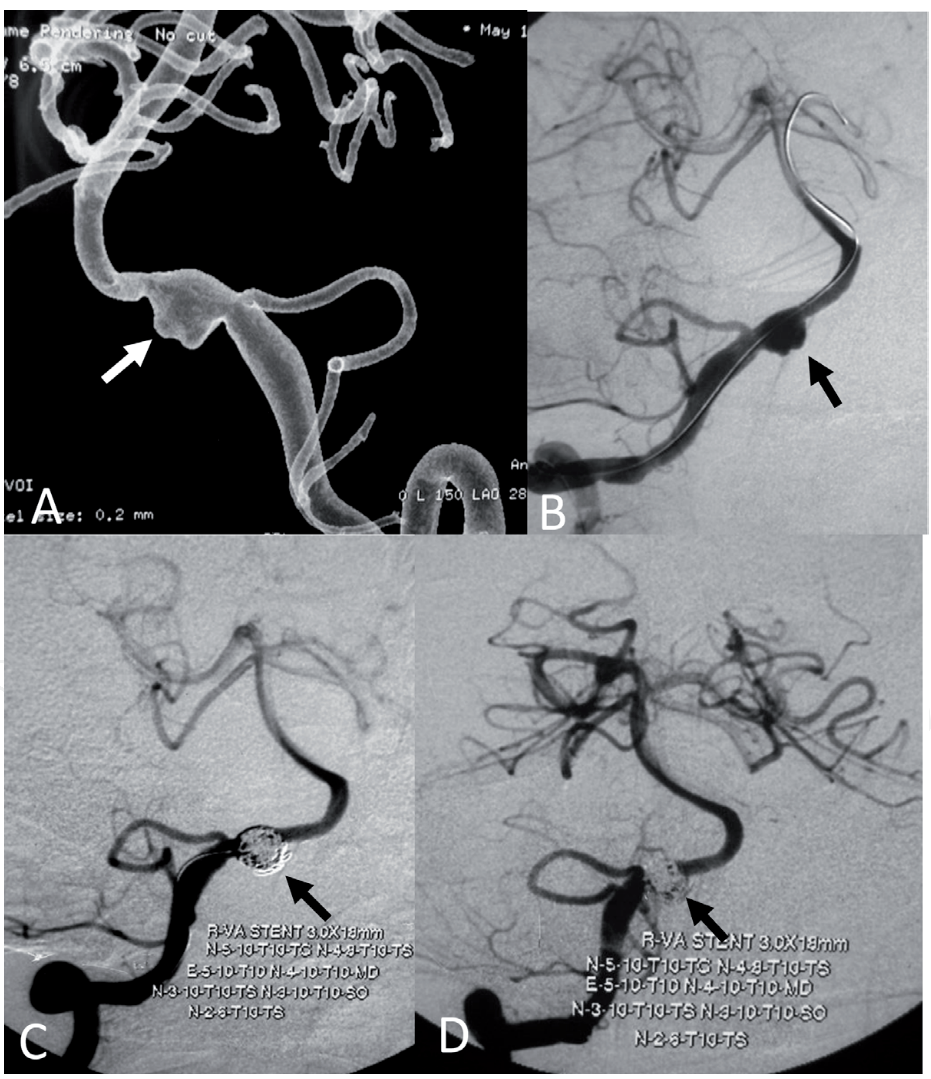


Figure 3.
A vertebral artery aneurysm treated with coronary artery stent and coiling in 1990s. A, 3-D angiogram of the right vertebral artery injection showing a dissecting aneurysm of vertebral artery-inferior posterior cerebellar artery (arrow). B, angiogram of the right vertebral artery injection showing a microwire was passed through the aneurysm for navigation of a BX coronary artery stent (Medtronic, USA). C, angiogram of the right vertebral artery injection showing the aneurysm was coiled with assistance of a 3.0 mm × 18 mm BX coronary artery stent (Medtronic, USA)(arrow). D, angiogram of the right vertebral artery injection showing the aneurysm was completely occluded (arrow).

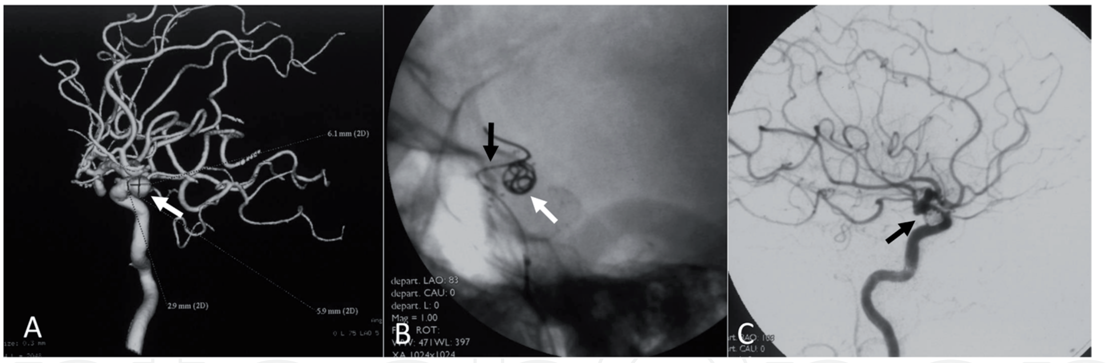


Figure 4.
A 62-year-old woman presented with an incidental paraclinoid aneurysm of the internal carotid artery. A, 3-D reconstruction of the right internal carotid artery injection showing the 6 mm × 6 mm paraclinoid aneurysm of the internal carotid artery (arrow), which was treated with 4 mm × 30 mm Neuroform stent and coils. B, the unsubtracted image showing the Neuroform stent (black arrow) and the first 3-D coil (white arrow). C, oblique view of the right internal carotid artery injection after treatment showing the aneurysm was occluded completely (arrow).

antiplatelet medication adding to the risk of the procedure itself as well as risks associated with the recovery period, these risks were quickly accommodated by interventionalists and improved overall occlusion rates as decreased the aneurysm recurrence (**Figure 4**) [27].

Bioactive coils were explored by some manufacturers to promote thrombus formation and endothelialization. However, these modified coils were shown to have limited efficacy and no clear advantage over pure platinum coils when used alone [28]. The use of polymers was also explored by some authors to treat cerebral aneurysms, but the increased risk and patient morbidity derailed this strategy and prevented its widespread acceptance [29].

It was firstly confirmed by the International Subarachnoid Aneurysm Trial (ISAT) that more and more aneurysm patients were being treated worldwide with the introduction of detachable coils and various intracranial stents [30]. An overall decreased risk of death and morbidity in the endovascular group treated with detachable coils when compared to those treated with open surgery were found [30]. The worldwide treatment of both ruptured and unruptured aneurysms by detachable coils quickly has surpassed open surgery as the primary treatment modality. Covered stents already are used successfully in the treatment of cerebral aneurysms, iatrogenic pseudoaneurysms, and carotid-cavernous fistulas (CCF) [31, 32].

4. Flow diverter

The introduction of flow diverter had a dramatic effect on the management of cerebral aneurysms. The concept of flow diverter was initially explored by Wakhloo in 2014, but Nelson and colleagues developed the first commercially available flow diverter [33]. Flow diverter introduced the concept of a more physiological therapy for aneurysms, focusing on treating the parent vessel without the requirement of entering the aneurysm dome [34]. With data that indicated complete occlusion rates that approached 90% at follow-up in systematic review, treatment recommendations for selected intracranial aneurysms was made [35]. Even giant aneurysms, in the past managed with balloon test occlusion and vessel sacrifice or complex bypasses, can now be managed with flow diverter with great efficacy and considerably lower morbidity [36, 37] (**Figure 5**). Moreover, the indications for flow diversion have been extended to smaller aneurysms that are usually treated with coiling, stent-coiling, or clipping [38].

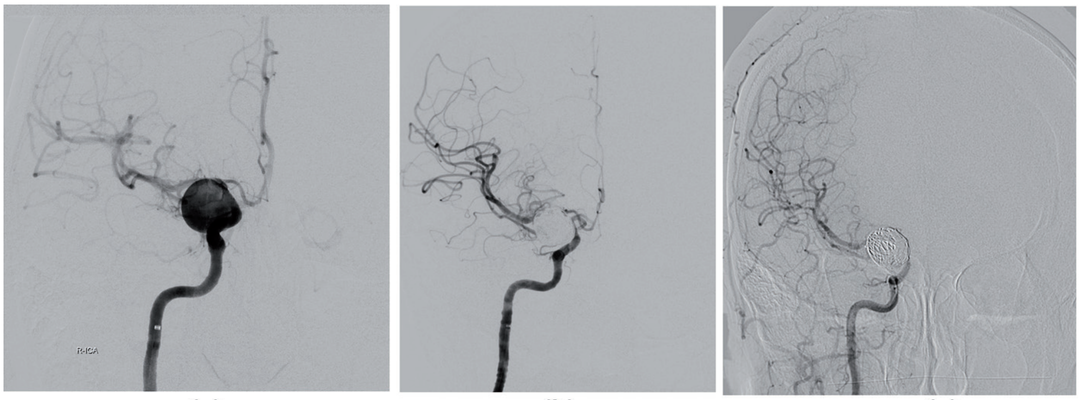


Figure 5.
A 58-year-old woman presented with visual deficit caused by a giant supraclinoid aneurysm of the internal carotid artery, which was treated by flow diverter. a, right internal carotid artery (ICA) angiogram (anteroposterior) demonstrating a giant aneurysm of the supraclinoid internal carotid artery. b, right ICA angiogram (anteroposterior) after pipeline flex flow diverter and coil embolization showing nearly complete occlusion of the aneurysm. c, right ICA angiogram (anteroposterior) at 1-year follow-up showing complete occlusion of the aneurysm.

Cerebral aneurysms, both ruptured and unruptured, can be treated with flow diverters [3]. Research into surface modification of devices to mitigate or negate the need for anticoagulation or antiplatelet medications is actively being pursued [3]. However, careful must be always taken in evaluating benefits and risks. In a recent paper by Gory et al., a total of 21.8% of interventions experienced at least 1 morbidity during the 12-month follow-up [39]. Among the serious events, 5.9% were considered permanent and related to the procedure. Moreover sixty-six (16%) of the 412 interventions had a complication, and 10 of them caused a neurological deficit [40].

5. Carotid-cavernous fistulas

Carotid-cavernous fistulas (CCF) are usually treated endovascularly by interventional neuroradiologists or neurosurgeons. The endovascular treatment strategies of CCF has dramatically changed with the evolution of endovascular neurosurgery. A series of treatment modalities have been traditionally attempted, including the carotid artery ligation or trapping, muscle embolization via cervical exposure of the carotid artery, and balloon embolization with or without carotid artery sacrifice [41]. Brooks reported successful closure of a CCF with a muscle embolus introduced surgically into the carotid artery in 1930 [42]. Serbinenko revolutionized the therapy for CCF in the 1970s by introducing detachable intravascular balloons [43]. Though these lesions were often treated with balloon test occlusion and vessel sacrifice in the early stage (**Figure 6**), CCFs are now almost exclusively treated by an endovascular strategy with preservation of the internal carotid artery. Balloon embolization of CCF through a transfemoral access with preservation of the distal ICA has reduced the morbidity related to the treatment. This method is the primary therapy in most cases of CCF [44]. In addition to the balloon embolization, several other modalities have been deemed useful in the treatment of CCF in recent years [45], such as detachable coils, covered stents, ethylene vinyl alcohol copolymer (EVOH) and flow diverter placement [45, 46] (**Figure 7**). Transvenous embolization via the inferior petrosal sinus, superior ophthalmic vein and EVOH embolization modalities have been used with success [46]. Spontaneous resolution and/or thrombosis of CCF has also been reported, especially in indirect CCF, but

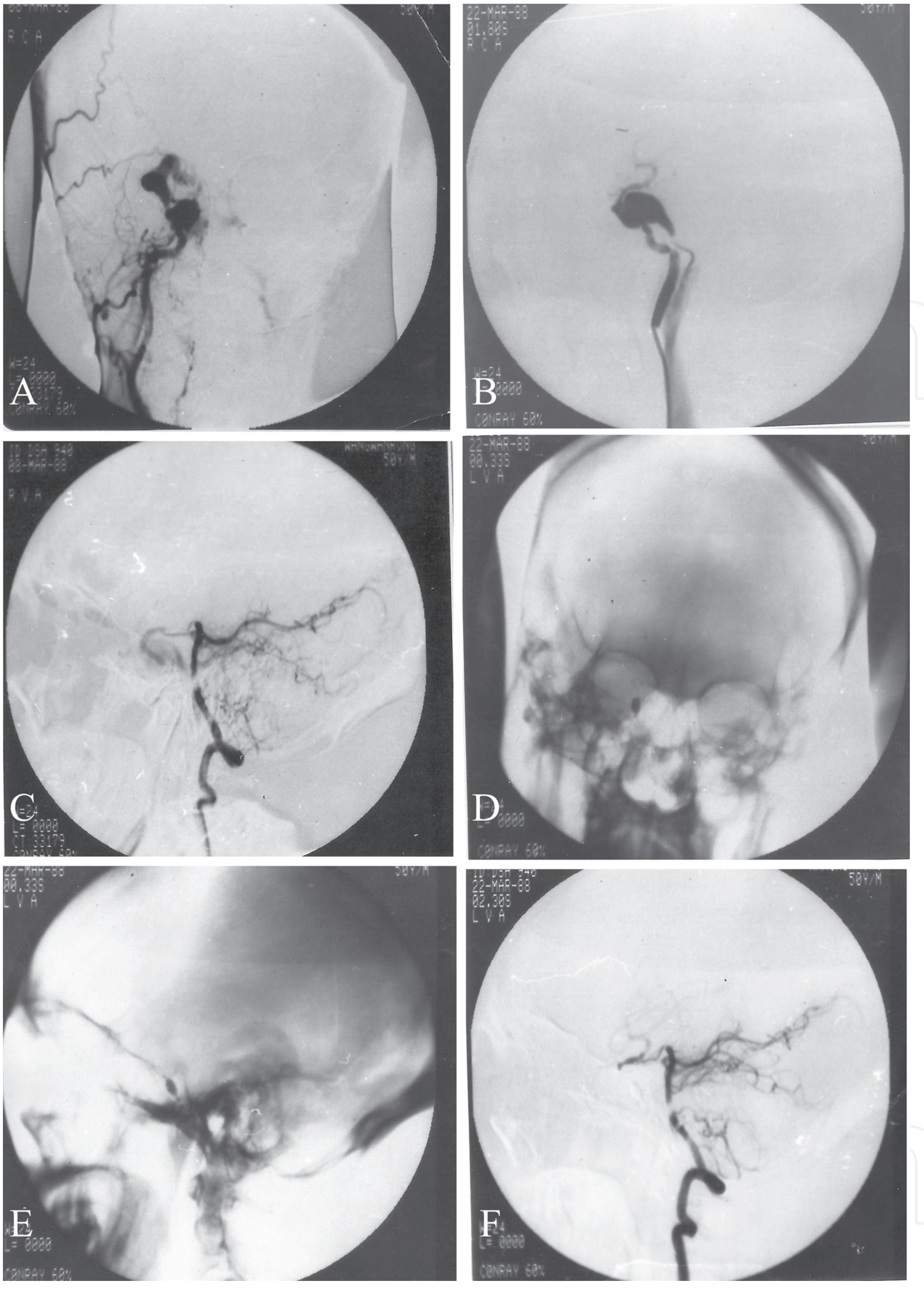


Figure 6.
A 50-year-old male patient of carotid-cavernous fistula was treated with detachable balloon in 1985. A, right internal carotid artery (ICA) angiogram (anteroposterior) and lateral (B) showing a direct carotid cavernous fistula and early opacification of right cavernous sinus with no antegrade flow beyond the cavernous sinus. C, left vertebral artery angiogram (lateral) showing opacification of right cavernous sinus. Because the patient had no neurological symptoms with no contribution from the right ICA, no balloon test occlusion was performed before sacrifice of the ICA. D, fluoroscopic view of the head (anteroposterior) and lateral (E) showing the placement of one detachable balloon in the ICA of fistula site. F, left vertebral artery angiogram confirming complete occlusion of the fistula with reconstitution of the distal ICA blood flow from the vertebral artery. No retrograde filling of the fistula is seen.

it is really rare. For less directly accessible lesions, superior ophthalmic vein access or direct puncture of the cavernous sinus and catheterization as an alternative approach to the cavernous sinus as well as transvenous routes can all be used [47].

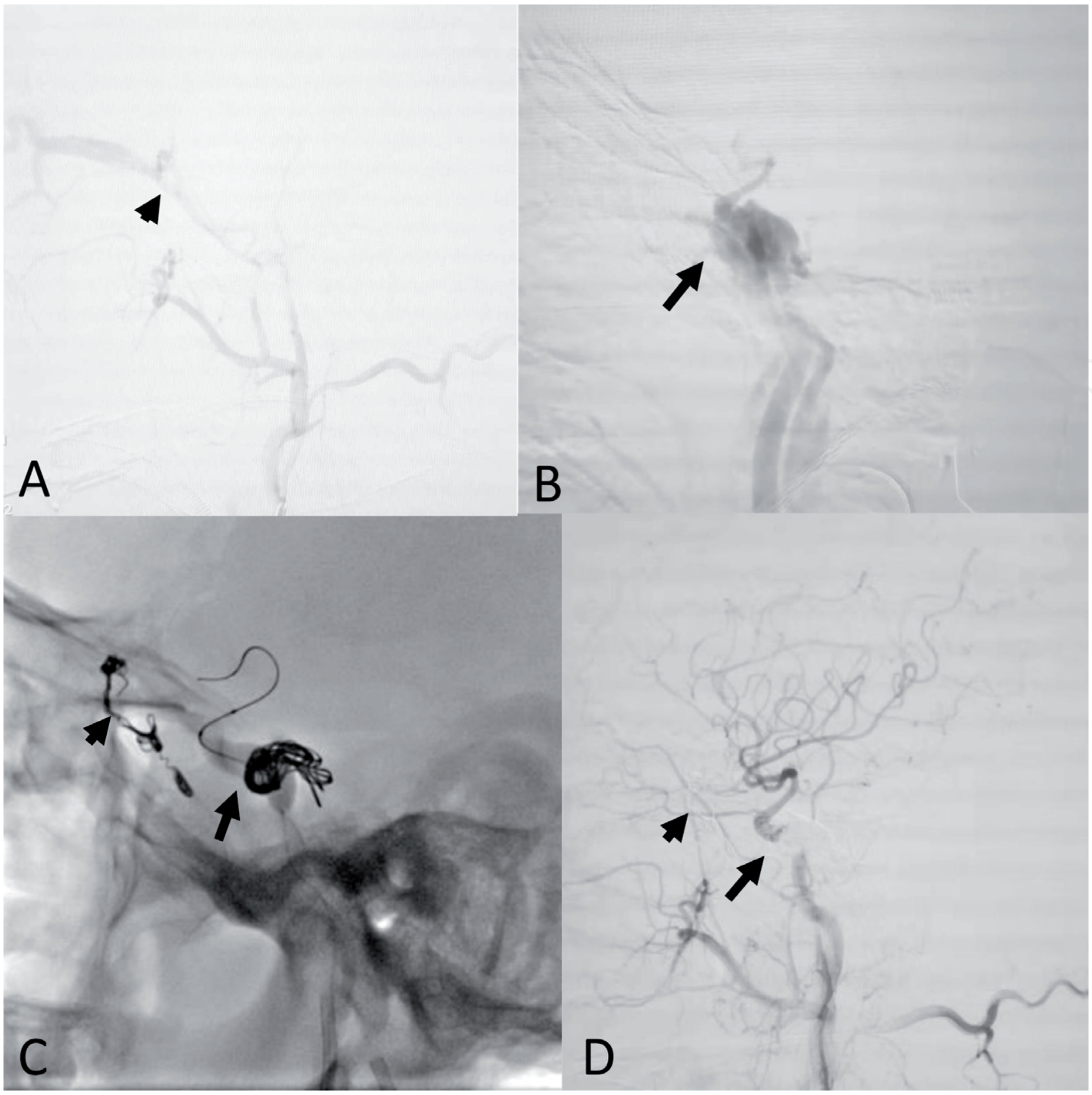


Figure 7.
A 33-year-old male patient of traumatic carotid-cavernous fistula was treated with preservation of the internal carotid artery. A, lateral view of the right external carotid artery showed an arteriovenous shunt between the anterior meningeal branch of the middle meningeal artery and the right superior ophthalmic vein (arrowhead). B, lateral view of the right carotid artery showed the high-flow carotid-cavernous fistula drained by the right superior ophthalmic vein and the right inferior petrosal sinus (arrow). C lateral view of unsubtracted image showed the inflated scepter C balloon (4 mm × 20 mm, Microvention, USA) in the right internal carotid artery (arrow) and the coils. Note the external carotid artery fistula was occluded with coils (arrowhead). D, lateral view of the left carotid artery angiogram after balloon-assisted onyx injection showed complete obliteration of the both fistulas and the intact left internal carotid artery.

6. Arteriovenous malformation

Exponential advances in catheter technology and refinements of embolic agents have greatly facilitated the rapid evolution of AVM embolization. In 1960's, Luessenhop and Spence performed the first embolization procedure on a cerebral AVM by surgically introducing silastic spheres made of methyl methacrylate into the ICA [48]. At that time, silk sutures, porcelain beads, Gelfoam, steel balls, Teflon-coated spheres, and polyvinyl alcohol were explored for AVM embolization with varying degrees of efficacy [49]. The use of these particle emboli was associated with a high complication rate secondary to inadvertent embolization of a normal cerebral vessel because the technologies and devices were not for direct nidus embolization.

Kerber developed the first calibrated-leak balloon, which allowed the direct embolization of an AVM nidus with the use of a rapidly solidifying polymer in

1976 [50]. This new system in combination with advances in imaging techniques and liquid embolic materials ushered in the modern era of AVM embolization. However, the use of calibrated-leak balloon catheters was associated with a high risk of arterial rupture. The introduction of liquid embolic agents, initially in the form of n-BCA, an acrylic adhesive [51], and advances in microcatheter and microwire design facilitated the distal catheterization of vascular malformations so that embolization of AVMs has evolved immensely over the last few decades to become a highly valuable therapy, and even an alternative in some cases, to surgery or stereotactic radiosurgery [52, 53]. The introduction of polymer non-adhesives (EVOH) allowed deep and extensive nidal penetration without the need for repeat distal catheterization and could be performed over long embolization procedure time periods [52].

Cerebral angiography detailed morphology study of the arteriovenous malformation involves evaluating the hemodynamic and anatomic characteristics of the lesion, including examination of the feeding arteries, the nidus itself, venous drainage of the lesion, coexisting aneurysms and arteriovenous fistulas [54]. A variety of strategies emerged, including multiple pedicle embolizations of the nidus. This was used by Lv et al. to "embolize AVM for cure" with low morbidity and mortality [55] (**Figures 8** and **9**). Endovascular surgery has specific indications in the treatment of AVMs, such as ruptured AVM, AVM of small size or deep locations, AVM with coexisting aneurysm and high flow fistula. Theoretically discussed and considered in the past, transvenous embolization is now being extensively explored, but its initial reports documented higher procedure-related hemorrhage rates [56].

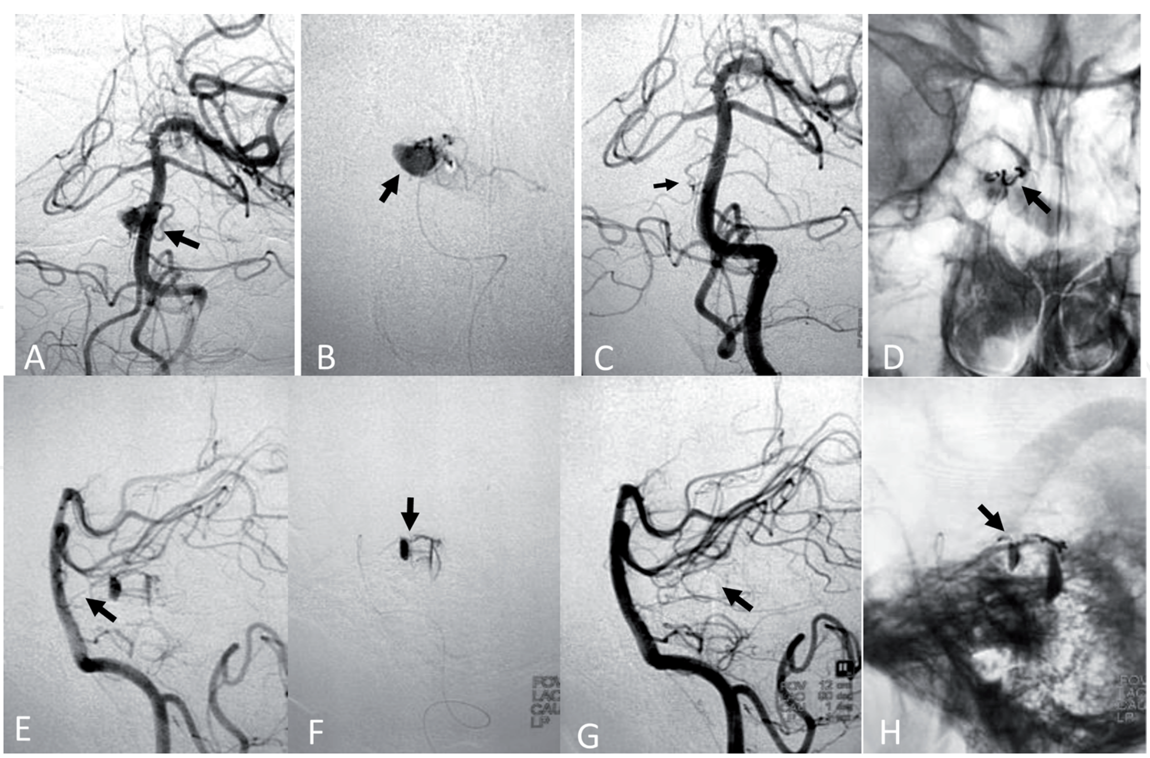


Figure 8.
A 40-year-old male patient presented brain stem hemorrhage caused by a small arteriovenous malformation. Anteroposterior angiography views (A-D) and lateral angiography views (E-H) . Showing a posterior pons arteriovenous malformation (AVM) fed by the left perforating artery of the basilar trunk (arrows in panels of a, E). Superselective angiogram demonstrating the ectasia of draining vein (arrows in panels of B, F). Angiograms after superselective onyx embolization showing complete disappearance of the AVM (arrows in panels of C, G). Postoperative images demonstrating onyx cast (arrows in panels of D, H).

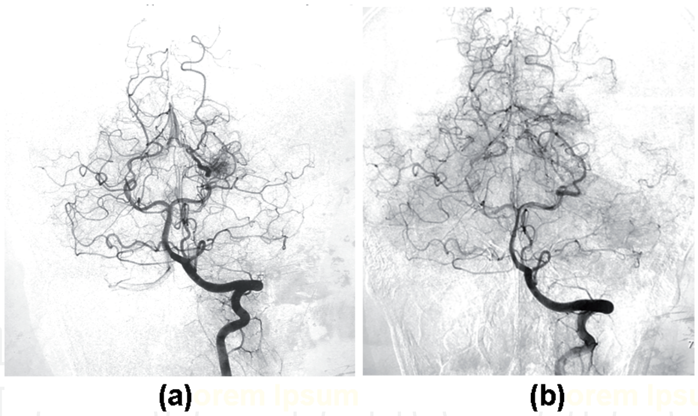


Figure 9.
A 5-year-old boy presented with intracranial hemorrhage caused by a small arteriovenous malformation. a, anteroposterior angiography of the left vertebral artery showing a small arteriovenous malformation (AVM) fed by the left posterior cerebral artery. b, anteroposterior angiography of the left vertebral artery after superselective onyx embolization showing complete disappearance of the AVM.

7. Vein of Galen malformations

Vein of Galen malformations are extremely rare lesions occurring in one out of a million live births [57]. They are treated almost exclusively with endovascular surgery. The lesions are amenable to endovascular embolization in the newborn presenting with heart failure or diagnosed in utero. An initial treatment stage is necessary and followed by additional staged embolization when the child is large enough to undergo more extensive embolization. Embolization strategies include closing the individual arteriovenous shunts or the initial venous side of the malformation.

8. Dural arteriovenous fistulas

Dural arteriovenous fistulas (DAVFs) represent a specific vascular lesion that incorporates the dural suppliers of the cranium or spine, contributing direct arterial shunting toward venous structures. Venous hypertension can lead to cortical

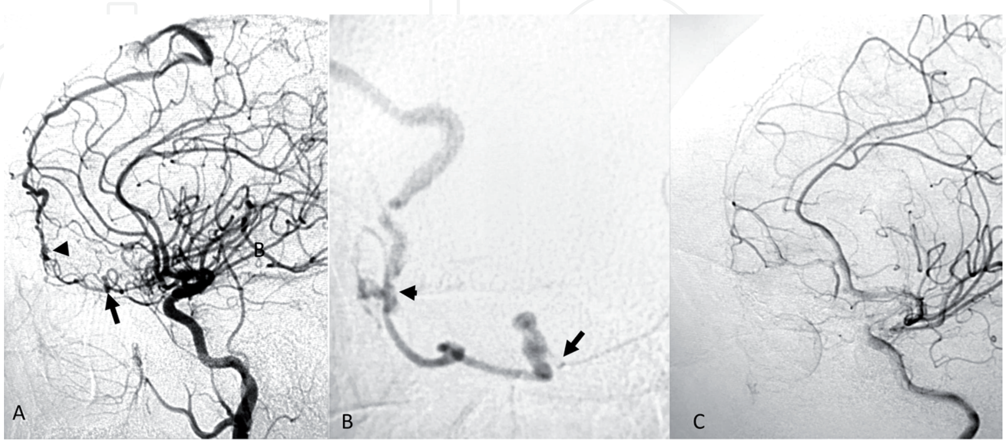


Figure 10.
A dural fistula fed by pial branches of the frontobasal artery was cured with onyx emblization. A, later internal carotid artery (ICA) angiogram showing a dural fistula fed by pial branches of the frontobasal artery and early opacification of frontal polar vein (arrowhead). Note the pseudoaneurysm on the feeding artery (arrow). B, superselective angiography by the microcatheter showing the pseudoaneurysm (arrow) and the fistula point (arrowhead). C, lateral internal carotid artery angiogram confirming complete occlusion of the aneurysm and the dural fistula.

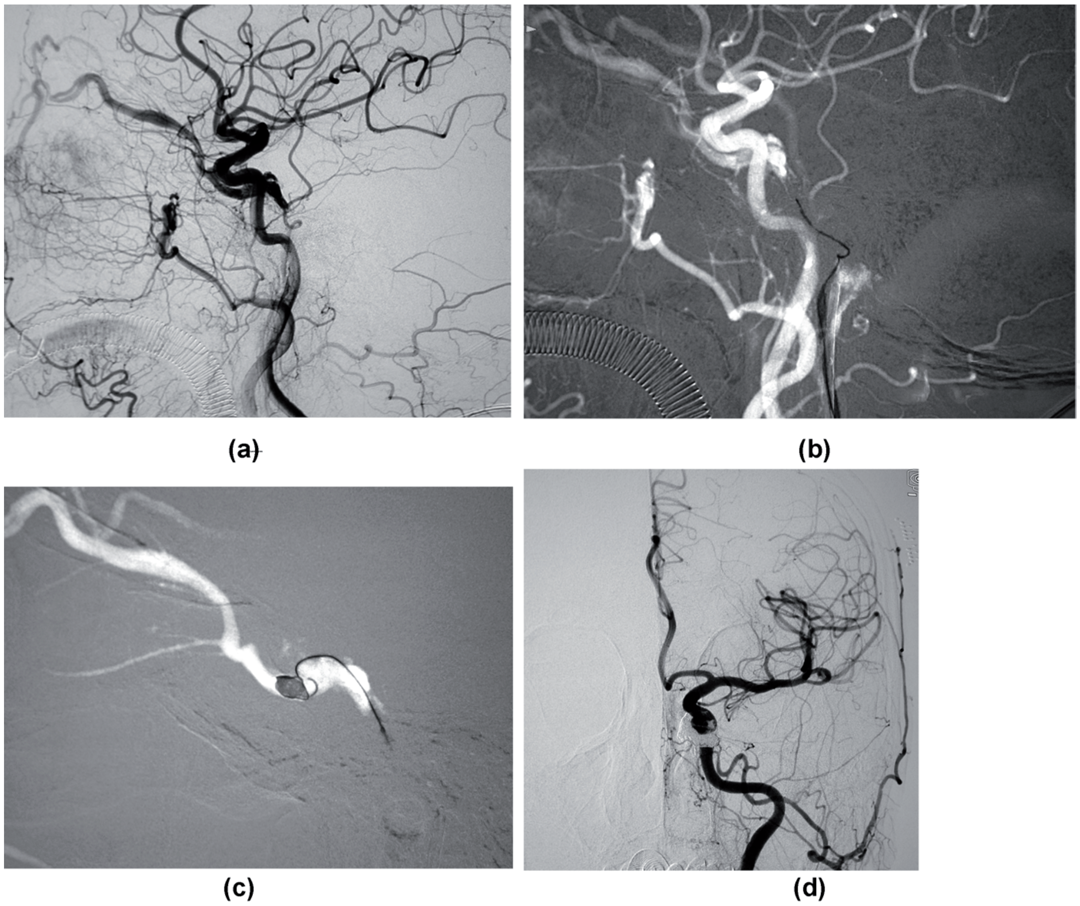
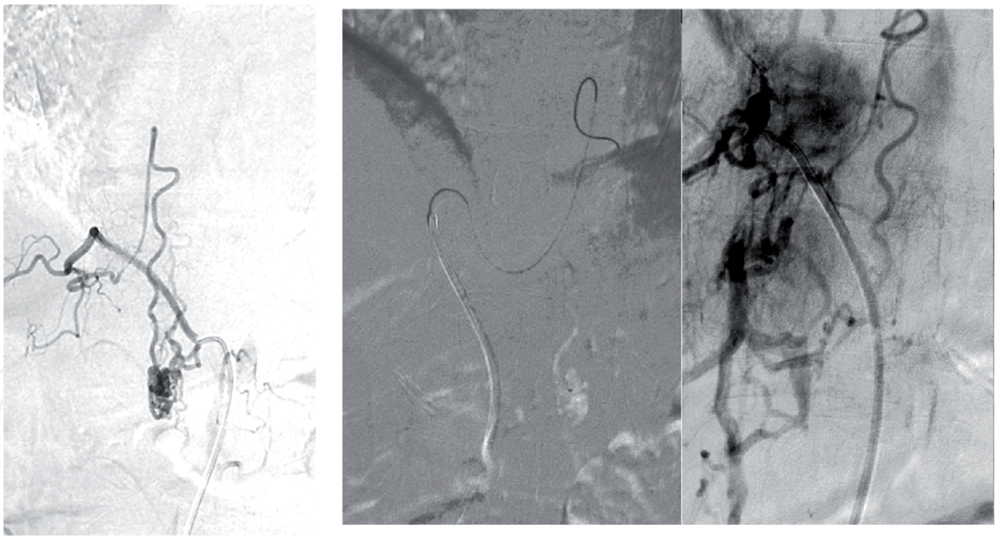


Figure 11.
A cavernous sinus dural fistula was cured with tranvenous access. a, lateral view of the left carotid artery showed the left indirect carotid-cavernous fistula drained by the left superior ophthalmic vein and the left inferior petrosal sinus was invisible. b, under roadmap image, the left inferior petrosal sinus was catheterized. c, under roadmap image, coils were delivered through the microcatheter in the left cavernous sinus through the left inferior petrosal sinus. d, frontal view of the left carotid artery showed complete obliteration of the carotid-cavernous fistula and the intact left internal carotid artery.

dysfunction, venous hypertension, and hemorrhage when DAVF occurs intracranially [58]. However, dilation of venous structures along the spinal cord can lead to myelopathy from tissue engorgement and venous hypertension as well as physical compression when DAVF occurs in the spine. The complex anatomy and points of arteriovenous shunting make their management complex. EVOH-based embolic materials have been proved to be useful in the endovascular obliteration of these lesions [59] (**Figure 10**). When these materials are combined with balloon catheters, a deep penetration to the point of arteriovenous shunts can be achieved [60]. Transvenous approaches are also routinely employed and highly successful when arterial access to the fistula point cannot be achieved (**Figure 11**) [61].

9. Spinal vascular malformations

Vascular lesions of the spine and spinal cord can be categorized into intramedullary and extramedullary lesions [62]. These lesions are rare and comprise a heterogeneous spectrum of diseases. They were first reported in the 19th century with the autopsy-based classification of Virchow and Picard [63]. However, it was in the 1970s, with the advent of selective spinal angiography, that they became better understood [64]. Their identification and localization have progressed significantly with the development of imaging techniques [65]. Several classification systems have been proposed over time to describe vascular lesions of the spine [66].



(a) (b) (c)

Figure 12.
A 49-year-old man presented weakness of two legs. a, left T-8 intercostal pedicle injection reveals the anterior spinal artery from above and below along the axis to supply the perimedullary fistula. b, under roadmap image a microcatheter was accessed to the fistulous point. c, control angiogram after onyx embolization reveals obliteration of the fistula with preservation of the anterior spinal axis.

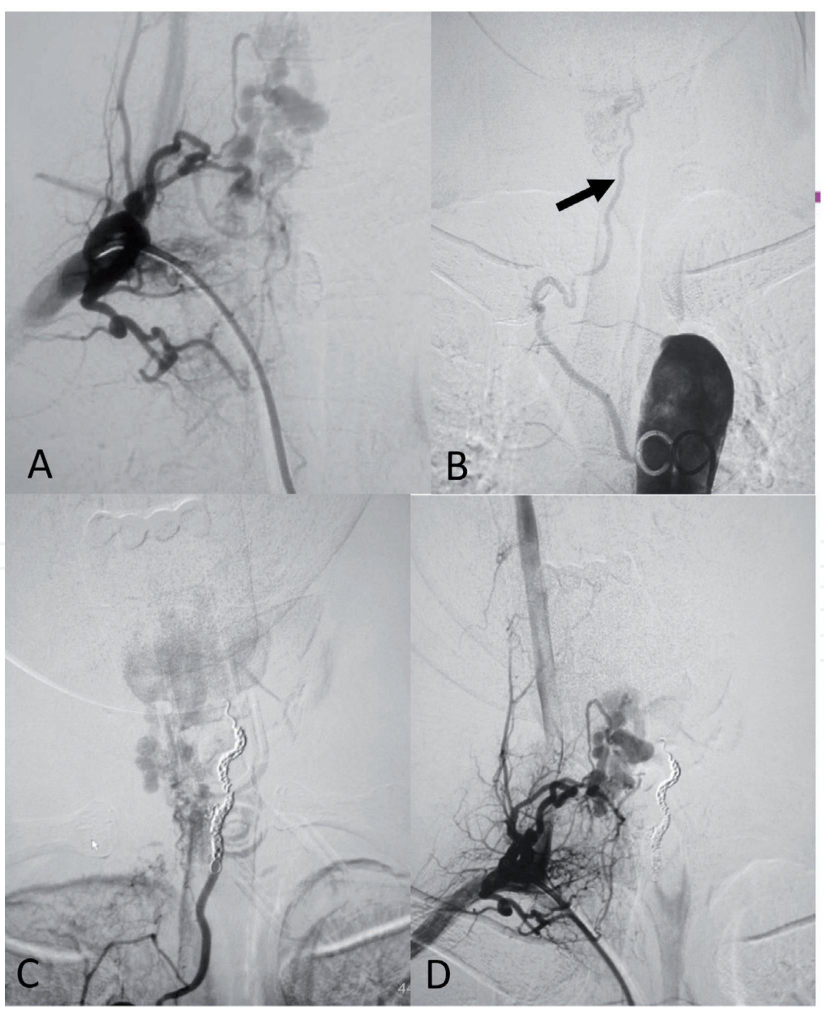


Figure 13.
A 37-year-old woman presented with SAH caused by a juvenile type spinal AVM. A, the right subclavian angiogram. B, aortic artery angiogram. Reveal supply to the AVM in the vertebra and the soft tissue around with feeders arising from right subclavian and intercostal arteries. After treatment, aortic artery angiogram (C) and the right subclavian angiogram (D), partial embolization with coils to reduce the venous congestion was performed through the left radiculomedullary artery (arrow).

The well known classification proposed by Anson and Spetzler in 1992 is type I, dural arteriovenous fistula (AVF); type II, glomus intramedullary AVM (**Figure 12**); type III, juvenile malformations (**Figure 13**); and type IV, perimedullary AVF [67]. With recent advances in embolic materials and devices in endovascular treatment, transarterial embolization plays an increasingly important role in the treatment of spinal AVMs. Complete angiographical obliteration of the nidus is not necessarily the goal of embolization, but rather, the treatment aims to reduce shunting volume and stabilize the symptoms [68].

10. Venous sinus stenting

Transvenous approaches have become quite useful in the treatment of dural sinus stenosis, often associated with a diverticulum of the sinus [69, 70]. With venous sinus stenting, promising results have been achieved in treating intracranial hypertension and venous stenosis–related pulsatile tinnitus. King et al. (1995) were the first to describe the venous stenosis through venography and manometry in intracranial hypertension but Higgins et al. became the first to stent the venous sinus in 2002 on a female with medically refractory intracranial hypertension [71]. Venography revealed bilateral transverse sinus stenosis and after stenting of one side, there was a significant improvement in trans-stenosis gradient and symptomatic control. Only in severe cases of cerebral sinus thrombosis that do not improve or deteriorate despite anticoagulant therapy, endovascular treatment would be considered.

11. Cerebral atherosclerotic stenoses

The development of angioplasty and stenting was influenced by the early work of endoluminal dilation of peripheral atherosclerotic disease. Until 1980, cerebral transluminal balloon catheter dilatation was reported to treat two patients with frequent, severe, progressive symptoms despite anticoagulation and high-grade intracranial atherosclerotic stenosis (ICAS) of the basilar artery [72]. The excellent angiographic and short-term clinical in these two patients and the prevalence of ICAS had favored further research of this approach. Unfortunately, frequent complications were reported in the next case series, including arterial dissection with consecutive thrombosis or rupture, residual stenosis due to sequestration or vessel recoiling and acute or subacute vascular occlusion due to the formation of a wall hematoma [72]. In order to reduce periprocedural complications of angioplasty alone, the rigid coronary Palmaz-Schatz stent was introduced for the first time in 1996 in a patient with recurrent TIA caused by severe ICAS of the right carotid artery despite antiplatelet and anticoagulant therapy [73]. The stent deployment led to a better angiographic result compared to angioplasty alone.

The first self-expanding, nitinol-composed Wingspan stent (Boston Scientific, Fremont, CA, USA) was approved by the US Food and Drug Administration (FDA) for patients with 50% or higher ICAS, symptomatic despite medical therapy in 2005 [74]. These patients might benefit from endovascular therapy since their plaques might not stabilize with best medical therapy alone and cause recurrent artery-to-artery embolic strokes. The development of new angioplasty balloon catheters and flexible stents has redefined the management strategy for symptomatic intracranial stenosis. A growing number of studies have reported a low complication profile and satisfactory rates of angiographic patency at follow-up [75].

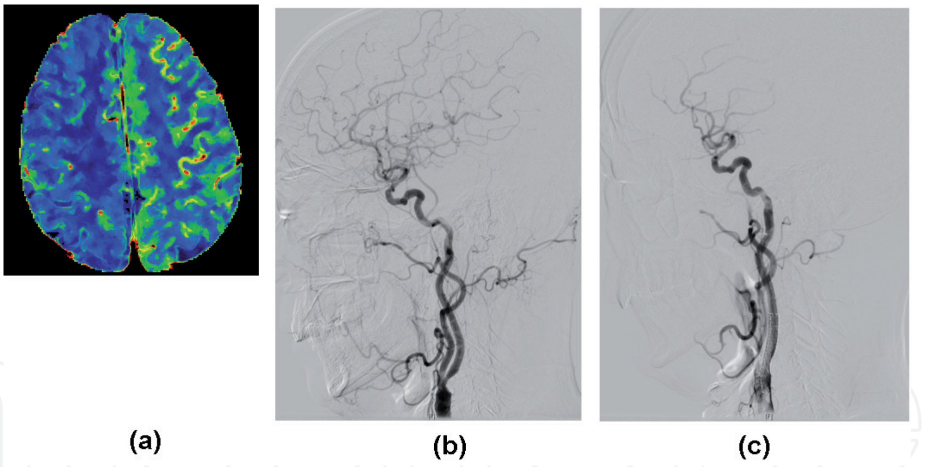


Figure 14.
A 79-year-old man presented with dizziness. a, CT perfusion image showing the low perfusion of the right cerebral hemisphere. b, right carotid artery angiogram showing the severe stenosis of the internal carotid artery. c, right carotid artery angiogram showing the stenosis was treated with angioplasty and stenting.

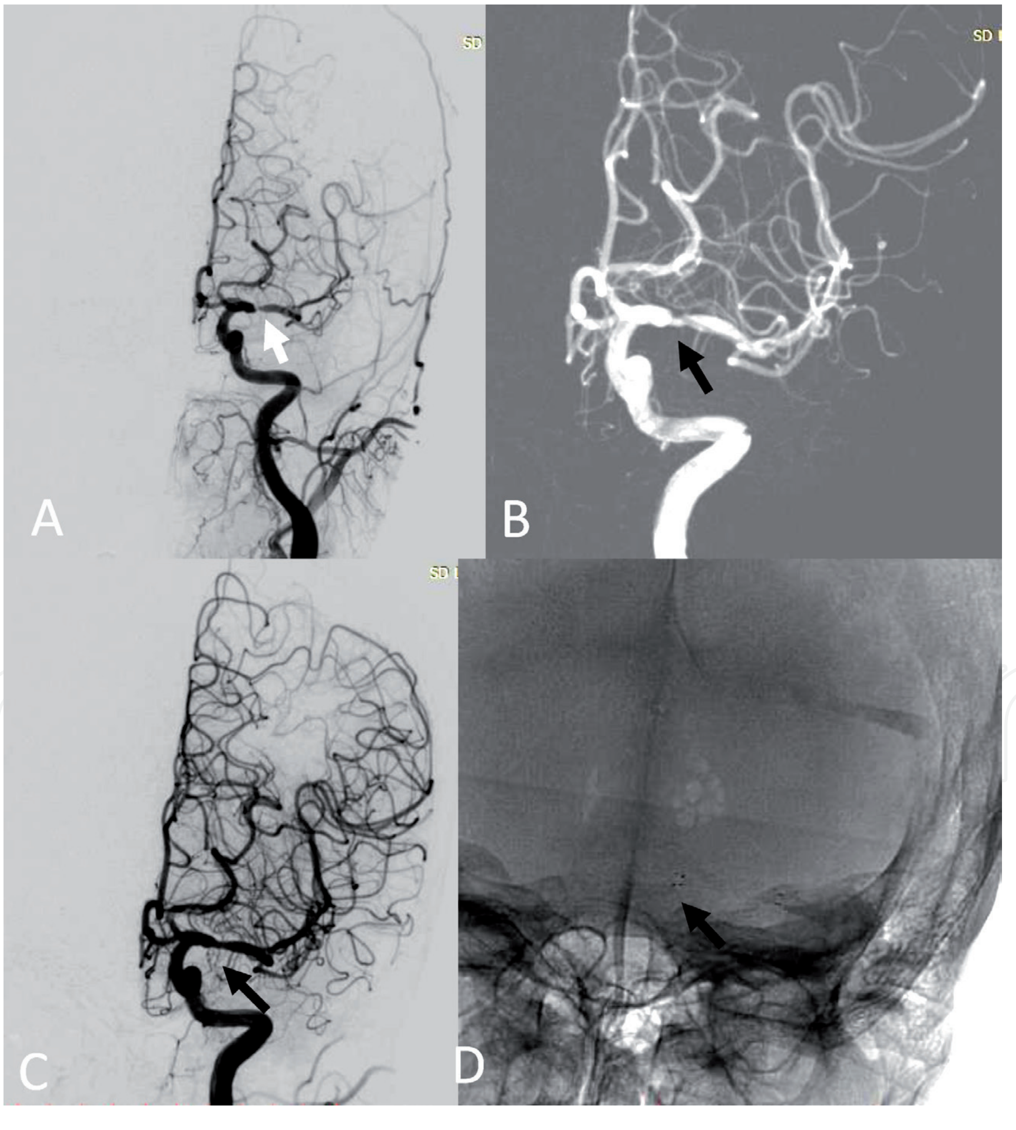


Figure 15.
A 64-year-old man presented with transient ischemic attack. A, left internal carotid artery (ICA) angiogram (anteroposterior) showing a severe stenosis of the M1 segment of the middle cerebral artery (arrow). B, under roadmap image showing a XT27 catheter (Stryker, USA) was advanced to the distal middle cerebral artery after balloon angioplasty (arrow). C, left internal carotid artery angiogram confirming the reconstitution of the middle cerebral artery (arrow). D, fluoroscopic view of the head showing the placement of a Neuroform EZ stent (arrow).

Angioplasty with stenting of carotid stenosis does not require general anesthesia and requires only a few seconds of carotid artery occlusion. Endoluminal revascularization has been proposed for the treatment of carotid stenosis in high-risk patients such as those with contralateral carotid occlusion [76], postendarterectomy stenosis [77], and/or severe coronary and other systemic diseases [78]. In a meta-analysis by Texakalidis et al. in 2018 including 13 comparative studies, compared to carotid artery endarterectomy carotid artery stenting had a lower incidence of cranial nerve injury, the two treatment approaches were similarly safe in terms of periprocedural stroke, myocardial infarction and death rates and carotid artery stent was associated with decreased restenosis risk (defined as either 60% or 70% stenosis) in the follow-up; however, without a significant difference in the risk of target lesion revascularization [79].

At present, we suggest that endovascular therapy may be considered as a treatment option for patients with recurrent ischaemic stroke despite best medical therapy and especially if pathophysiologically attributed to hypoperfusion with/without bad collaterals [80] (**Figures 14** and **15**). In future, better experience of interventionalists and improved features of stents deployed are also expected to boost outcome of endovascular therapy in ICAS.

12. Thrombolysis and mechanical thrombectomy

Before 1995, stroke therapy consisted exclusively of supportive management and efforts to prevent recurrence [81]. In 1995, the National Institute of Neurological Disorders and Stroke reported that early intravenous thrombolysis using tissue plasminogen activator was more effective than placebo [81]. The use of Alteplase for acute ischemic strokes was approved by The Food and Drug Administration (FDA) in 1996 [82]. Thrombolytic therapy was initially offered to eligible patients up to 4.5 hours from symptom onset. IV Alteplase was determined not to be as effective a therapy for patients with large vessel occlusions although it was proved to be an effective treatment. The concept of intraarterial pharmacologic thrombolysis was further expanded and solidified in 1999 with the completion of the Prolyse in Acute Cerebral Thromboembolism study [83]. Intravenous thrombolysis and intra-arterial thrombolysis received widespread acceptance and truly revolutionized the management of acute stroke.

Mechanical thrombectomy has transformed our field, leading to an explosion in intervention for large vessel occlusion. Endovascular thrombectomy became the standard of care of the large vessel occlusion as a result of 5 randomized control trials (RCTs) in 2015 [84]. These 5 trials, MR CLEAN, ESCAPE, SWIFT PRIME, EXTEND-IA, and REVASCAT, extended the field of endovascular neurosurgery. These RCTs proved that patients who had improved functional outcome scores at 90 days after thrombectomy with successful recanalization [84]. This was compared with patients who received IV thrombolytic therapy alone or were unable to receive IV thrombolytic therapy. Improved functional outcomes were also demonstrated by two additional landmark trials, DAWN and DEFUSE [85]. Endovascular thrombectomy for large vessel occlusion beyond the window of 3 to 4.5 hours has provided new treatment options and supportive data demonstrating improved functional outcome scores. Patients meeting eligibility criteria for mechanical thrombectomy had no additional risks in the extended window of 16 to 24 hours. The second generation of devices, including stent retrievers and aspiration catheters, has demonstrated a significantly improved safety, revascularization, and patient outcome. Therefore, the criteria for mechanical thrombectomy, including time limit and physiological preconditions should be re-examined. Not only were time limits extended, but also discussions on the ability to preserve additional tissue at risk, even in the setting of an established stroke, have made stroke intervention a significant part of the foundation of endovascular practice. "Stroke center," "mechanical thrombectomy ready," and "comprehensive stroke center" designations have all been applied.

13. Tumor embolization and intra-arterial chemotherapy

Direct vascular access to brain tumors both benign and malignant has been exploited since the 1970s [86]. Preoperative embolization can facilitate resection and decrease intraoperative blood loss in the treatment of meningiomas. As with all endovascular strategies, keen understanding of the vascular anatomy is required to prevent unnecessary risk. Over the past few years, intra-arterial chemotherapy for more malignant tumors, such as gliomas, has had a resurgence. In future, the new neuro-pharmaceutical/chemotherapy/immunotherapy drugs, which could be delivered intra-arterially, will be developed [87].

14. Subdural hematoma embolization

Chronic subdural hematoma may be one of the most common neurological conditions requiring treatment in the future because of an aging population and the regular use of antiplatelet and anticoagulation medications. Chronic subdural hematoma has been managed with craniotomy and/or drainage both operatively and at the bedside. Embolization of the middle meningeal artery supply to the dura and subdural membranes as a renewed treatment of chronic subdural hematoma has been originally described by Japanese neurosurgeons almost 20 years ago [88]. The technique can be used as a rescue technique in patients who have undergone previous craniotomy as well as a primary treatment in patients with significant comorbidities. Particle embolization and liquid embolic agents have demonstrated excellent results in recent publications [89]. These encouraging results suggested the need for a large prospective randomized trial to investigate the true role of middle meningeal artery embolization as a stand-alone treatment for chronic subdural hematoma.

15. Resident and fellowship training

The expansion of endovascular techniques has led to a need to train neurosurgical residents in the application of endovascular therapies, just as they would learn newer techniques in spine or tumor neurosurgery. The Neurosurgery Residency Review Committee and American Board of Neurological Surgeons (ABNS) have correctly made regular adjustments in the area of endovascular case minimums for neurosurgery residents not only to include cerebral angiography, but now also to include more complex intervention experience, such as aneurysm coiling [90].

The future of endovascular neurosurgery would be inseparable from the future of neurosurgery. Residents interested in the vascular disease processes that affect the central nervous system must understand the application of neuroendovascular techniques and if they want to treat these pathologies must be adequately trained in their implementation. In Japan and China, most endovascular surgery is carried out by neurosurgeons who carry out cerebral and spinal cord angiography and interpret the images obtained. This experience not only increases their knowledge of vascular anatomy, but also improves their surgical acumen.

We agree with Peschillo et al., who put forward that vascular neurosurgeons cannot perform surgery and endovascular treatment at the same time [91]. To be precise, in order to provide the best treatment for patients, the two members of vascular neurosurgeon and endovascular neurosurgeon must clearly realize that the other side can make up for their technical weaknesses, and at the same time, they should form technical complementarities to deal with the advantages and disadvantages of surgical and endovascular treatments. In order to remain at the forefront of the assessment and treatment of patients with neurovascular diseases, vascular neurosurgery must develop towards a professional direction, mastering the knife and catheter. It is the time for neurosurgeons to start training residents of endovascular neurosurgery, just as we train neurosurgeons in other neurosurgery disciplines.

16. Conclusion

Endovascular neurosurgery provides management of neurovascular conditions encountered in clinical practice, such as aneurysms (with or without subarachnoid hemorrhage), AVMs, dural AVFs, and carotid disease. The success of endovascular thrombectomy for large vessel occlusion is now irrefutable, making it an accepted standard of care. Endovascular treatment of cerebral aneurysms is no longer limited to primary coiling but now includes options such as stent or balloon assistance, flow diversion, intrasaccular and bifurcation-specific devices. Balloons, liquid embolic agents, and distal access catheters have updated the treatment of arteriovenous malformations and fistulae. The evolution of the neuroendovascular field has resulted in the development of program requirements for residency or fellowship education in endovascular neurosurgery.

Author details

Xianli Lv, MD
Neurosurgery Department, Beijing Tsinghua Changgung Hospital, School of Clinical Medicine, Tsinghua University, Beijing, China

*Address all correspondence to: lvxianli000@163.com

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