# Complications and Avoidance in Neurointerventional Surgery

Girish Rajpal[1] Noufal Basheer[2]

[1]Neurointerventional Surgery, Max Hospital, Delhi, India
[2]Neurosurgery, MIMS-ASTER, Kozhikode, Kerala, India

**Address for correspondence** Girish Rajpal, Head, MCh, AFSA, Neurointerventional Surgery, Max Hospital, PPG & Vaishali, Delhi 110092, India (e-mail: drgirishrajpal@live.in).

Indian J Neurosurg 2018;7:90–95

**Abstract**

Because neurointerventional surgery is a minimally invasive technique does not mean that it is qualified for complication-free procedures. Rather working about 2 m away from the three-dimensional (3D) target lesion and looking at two-dimensional (2D) images makes it one of the most complication-prone subspecialties. Advancement in hardwares, techniques, and technologies with continuous ability to learn and modify accordingly can only keep the complication rate low as compared with traditional vascular neurosurgery.

**Keywords**
- complications
- neurointervention
- thromboembolism

## Introduction

The endovascular approach to the central nervous system began just a few decades ago and has become a very important tool in the arsenal of neurosurgeons. This has become one of the rapidly evolving specialties of medicine. In the early days, endovascular procedures involved usage of crude hardwares, lengthy surgical time, and lot of complications. Any injury to the cerebral vasculature results in catastrophic outcome with major morbidity and mortality. Even though a lot of advancements have taken place in techniques and technologies over the time, the specialty still remains in infancy and complications still result in major clinical disasters.

Complications associated with neuroendovascular therapy are common and vary with the status of the lesion being treated.[1] Overall complication rates are around 20%, with a 1-month mortality rate estimated at 1.4%.[1,2] The most commonly reported complications in endovascular neurosurgery include thromboembolic events, groin-site hematoma, contrast-induced nephropathy, intraoperative rupture, failure to treat lesion, and radiation-induced effects.[3] We focus this review on complications common to both diagnostic and therapeutic procedures of neurointervention, as thorough knowledge will help the endovascular surgeon anticipate problems and thus help in avoiding them.

## Complications Related to Vascular Access

Femoral access is still the most common mode of vascular access for neuroendovascular procedures, though in some selective cases, transradial access can be opted. The femoral artery, in most of the population, is a larger caliber artery (permitting larger-size catheters) and is less prone to spasm when compared with the radial artery.[4] Recognition of access site complications and early treatment of these complications can prevent more serious complications and death. Complications include groin hematoma, retroperitoneal hemorrhage, formation of pseudoaneurysm and arteriovenous fistula, arterial occlusion leading to ischemic limb, femoral neuropathy, and infection. Complications for diagnostic procedures are lower due to use of smaller-sized sheaths and shorter duration of procedure.[5,6] Wagenbach et al, in their recent series of almost 300 patients who underwent diagnostic and therapeutic neuroendovascular procedures, report a rate of 1% incidence of groin hematoma.[7] Severe groin hematomas require surgical intervention for definitive therapy, and if left untreated, may progress to retroperitoneal hematoma, which can be catastrophic. Looking for peripheral pulsation (dorsalis pedis artery, posterior tibial artery in femoral puncture) pre- and postprocedure is always recommended.

Incorrect site of the femoral artery puncture is the most common cause of these complications. Puncturing below the femoral bifurcation is usually the reason for pseudoaneurysm

**received**
May 31, 2018
**accepted after revision**
July 9, 2018
**published online**
September 5, 2018

**DOI** https://doi.org/10.1055/s-0038-1669479.
**ISSN** 2277-954X.

formation, groin hematoma, and arteriovenous fistulas, whereas retroperitoneal hemorrhage (incidence of < 3%) is caused by femoral punctures above the level of inguinal ligament.[8–10] Early identification of bleeding and vascular complications is important as these complications are associated with adverse events. A thorough knowledge of the surface anatomy of femoral artery and its application along with the use of ultrasound scan or fluoroscopy for guidance of femoral punctures can reduce these complications.[11–13] Furthermore, the micro puncture technique has been shown to reduce complications but is not widely adopted.[14] Radial puncture for the vascular access is on the rise among the interventionists, and few studies have shown that it is associated with significantly lower complications.[15] Problem with radial access is difficult navigation into the carotid system.

To reduce access-related complications, one should avoid areas of previous surgery (such as hip replacement or hernia repair) or a lower extremity in which vascular repair has been performed. In most centers, manual compression is given at the puncture site to avoid groin-site hematoma and its related complications. Care should be taken to access the femoral artery at a compressible site below the inguinal ligament (►**Fig. 1**). Puncture site closure devices, including collagen plugs, percutaneous devices, and external compression devices, have become popular recently to prevent access-related complications[16–18] though concrete evidence regarding their benefits in reducing complications is still lacking.

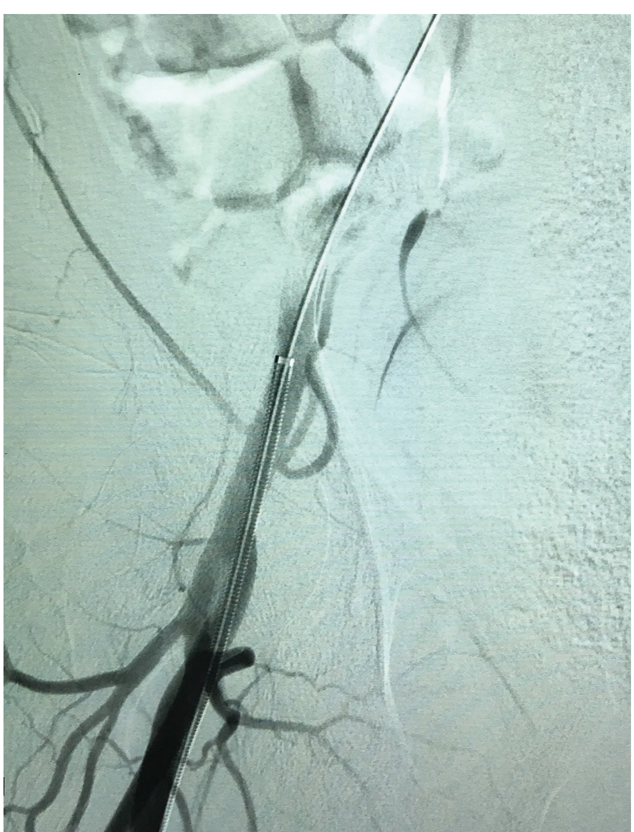

**Fig. 1** Ideal site of femoral puncture between the femoral bifurcation and inferior border of inferior epigastric artery.

## Vasospasm and Dissection

Placing and navigating even a guiding catheter during neurointervention procedure may cause vasospasm or, in severe cases, dissection (►**Fig. 2A**). It is always better to avoid such scenario by using nimodipine infusion in flush bags, or if it occurs, then by slowly injecting nimodipine or 50 to 100 µg nitroglycerine through guiding catheter. In severe cases of dissection of internal carotid artery, stent deployment remains the only resort (►**Fig. 2B**).

## Thromboembolic Events

The reported incidence of hyperacute thromboembolic complications is seen to vary between 3 and 11% in previous series.[19–21] Incidence depends on rupture status of the treatment target, mode of detection of the event, and type of procedure performed.[22,23] Carotid artery stenting has got higher intraprocedural thromboembolic rates, with significantly higher risk in patients with symptomatic lesions. Iatrogenic dissection, catheter-induced vasospasm, and operative technique account for most of these events. Patients older than 60 years, those with cerebrovascular disease, and those with longer procedure times are also at greater risk.[24] Thromboembolic complications induce perioperative morbidity. Therefore, avoiding thrombus formation during endovascular treatment is important. Though reported thromboembolic episodes are high, persistent neurologic deficits occurred only in 2 to 5% of the patients.[21] In one study, stroke rates at 30 days after the procedure is around 5%.[22]

In current practice, many strategies are used for prevention of thromboembolic events. A carefully titrated systemic heparin therapy to keep activated clotting time (ACT) between 250 and 300 with varying treatment duration before, during, and after the procedure is the most commonly used strategy. Aspirin and clopidogrel are routinely used for thromboembolism prophylaxis in patients undergoing stent placement.[25] Although the combination helps in preventing thrombotic complications in stent placement, some patients do not respond to clopidogrel and have a higher risk of stent thrombosis. Sedat et al studied the efficacy of prasugrel, another platelet inhibitor and an irreversible antagonist of $P2Y_{12}$ ADP receptors, and found that it reduces the clinical consequences of thromboembolic complications of endovascular treatment with stenting and


**Fig. 2** (**A**) Dissection with guiding catheter. (**B**) Stent deployment.

coiling of unruptured intracranial aneurysms.[26] Ticagrelor is a new reversible ADP P2Y12 platelet receptor inhibitor with no known resistance that will be help in clopidogrel-resistant patients. Yamada et al,[27] in a study of 369 consecutive aneurysm coil embolization cases, retrospectively noted that patients who had been treated preprocedurally with clopidogrel and/or aspirin had significantly fewer thrombotic complications than those who received antiplatelet therapy only postprocedurally or those who received no antiplatelet therapy (1.9% vs. 2.3%, and 16%, respectively). However, in ruptured aneurysms, benefits of antiplatelets has to be carefully weighed against the risk of hemorrhagic complications related to other procedures, such as ventriculostomies, and devastating consequences of intraprocedural rupture (IPR) or rerupture of the aneurysm prior to its complete repair.

A variety of rescue therapies have recently been applied when embolism occurs. Intraprocedural administration of abciximab and other glycoprotein IIb-IIIa inhibitor were used in small uncontrolled series with some good effect. Treatment with another glycoprotein IIb-IIIa inhibitor, tirofiban and eptifibatide, has also been reported in uncontrolled series to be safe and effective for dissolving intraprocedural clots[28,29] (►**Fig. 3A, B**). Ries et al analyzed the effect of a modified intraoperative anticoagulation strategy including intravenous acetylsalicylic acid (ASA) (not available in India) on complication rates during endovascular coil embolization. They found that intravenous ASA was associated with a significant reduction in the rate of thromboembolic events without increase in the rate or severity of intraoperative bleedings.[30] In few instances where complete occlusion occurs, stent retrievers will help in restoration of the flow (►**Fig. 4A–D**).

Air embolism, also a feared complication (►**Fig. 5**), deserves mention as there are various preventive strategies that can be used. Making sure of an airless flush bag and line system at the beginning of the procedure may be a useful component of endovascular safety measures to prevent air embolism.

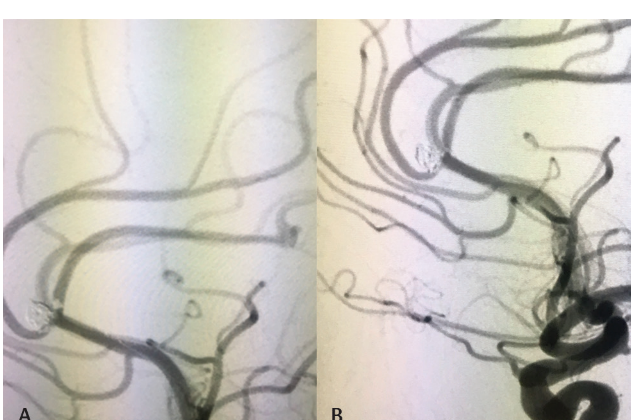


**Fig. 3** (**A**) Post coiling thrombus formation in callosomarginal artery. (**B**) Same patent after infusion of G IIb-IIIa inhibitor.

## Contrast-Induced Complications

Contrast-induced nephropathy is a is a serious complication of angiographic procedures resulting from the administration of contrast media with an incidence of less than

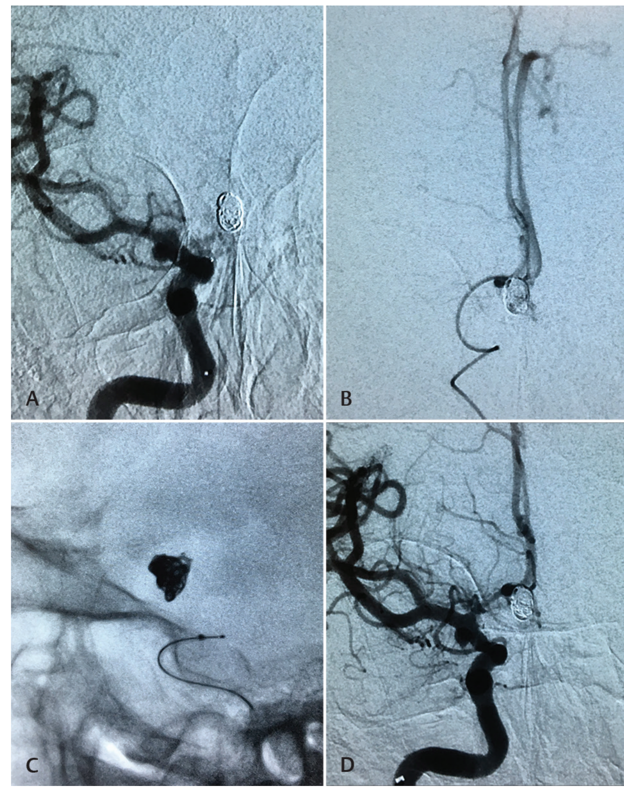


**Fig. 4** (**A**) Complete occlusion of right A1 post Acom aneurysm coiling. (**B**) Microcatheter placement beyond occlusion site. (**C**) Placement of stent retriever. (**D**) Complete reperfusion post clot retriever.

**Fig. 5** Air embolism in posterior cerebral arteries.

5% in low-risk patients and 20 to 30% in high-risk patients after contrast administration.[31] Risk factors include contrast-related factors such as high osmolar content, ionic contrast agents, and high viscosity and high contrast volume. Patient-related factors include chronic kidney disease, diabetes mellitus, older age, and other cardiovascular risk factors. It is defined as an elevation of serum creatinine of greater than 25% or 0.5 mg/dL or greater from baseline within 48 hours. Good hydration during the procedure and of *N*-acetylcysteine or bicarbonate and use of iso-osmolar and nonionic contrast have been proposed as nephroprotective strategies.[32,33]

In the presence of risk factors, alternative imaging techniques should be considered first if the risks are thought to be outweighed by the benefits of contrast administration. When possible, nonsteroidal anti-inflammatory drugs should be withheld for at least 24 hours before and after the procedure, and metformin should be avoided for at least 48 hours before the procedure. It should not be restarted until it is clear that contrast-induced nephropathy has not developed after the procedure. Sodium bicarbonate and *N*-acetylcysteine may have beneficial effects,[34,35] but no conclusive evidence has been found so far.[36–38]

## Intraprocedural Rupture

The most feared and fatal complication of endovascular surgery is the dissection of the vessel or rupture of an aneurysm. Reports of its incidence range from 1 to 9%.[19,39,40] Patients who have IPR during coiling usually fare worse than those who experience this complication during open surgery, as the resulting bleeding cannot be immediately evacuated, and all efforts are aimed solely at trying to repair the leakage, potentially even at the cost of vessel sacrifice. The CARAT (Cerebral Aneurysm Rerupture After Treatment) study done at nine high-volume centers in the United States included 1,010 ruptured intracranial aneurysms. They compared the rupture rates in patients treated with coiling and clipping and found a 5% risk of IPR in the coiling group with an attendant 64% rate of death or disability compared with a 31% rate of death or disability among patients who experienced an intraoperative rupture during open surgical clipping.[41] Risk factors for intraoperative rupture during occlusion of aneurysms include small aneurysm size, recent rupture, and the presence of a daughter sac. Another study by Park et al showed an incidence of IPR in 7.5% (6/80) in ruptured aneurysms and 2.5% (4/155) in unruptured aneurysms.[42] They concluded that independent risk factors for IPR during endovascular treatment of intracranial aneurysm were aneurysm size and anterior communicating artery aneurysm.[42] Ruptured aneurysms showed a higher tendency toward IPR than did unruptured aneurysms. Aneurysms with a sharp angle between the parent vessel and fundus also had a higher incidence of rupture. The aneurysm can be perforated through the dome by a guidewire or microcatheter. An aneurysm can be entered with the microwire sheathed inside the microcatheter, and this may reduce the risks of perforation. Distal curve in the microcatheter and microwire may reduce the chances of impinging directly on the wall. Coils themselves may cause rupture even if soft coils are used. This most commonly occurs during deployment of last coil and rupture may occur either at the neck or the dome.

In the case of aneurysm rupture during procedure, the management consists of immediate reversal of the heparin using protamine sulfate in the dose of 1 mg of protamine for 100 units of heparin, continuing with the originally planned coil embolization process and placing coils in the subarachnoid space and in the aneurysm. This may not be successful in some cases as the placement of coils may further increase the size of the rent in the aneurysm. It is better to have balloon in place in case of such catastrophes, especially during initial few cases. Placement of an emergency external ventricular drain may help in reducing the intracranial pressure. In some cases, vessel may have to be sacrificed.

Vessel rupture during arteriovenous malformation (AVM) embolization may occur when perforation of a feeding or draining vessel is caused by the microwire or microcatheter. Rescue therapy may consist of immediate injection of embolization material unless the injury is too far upstream.[43] Improvements in access and embolic devices with proper endovascular techniques in experienced hands all contribute to minimizing the risk of intraprocedural aneurysm rupture.

## Failure to Treat Lesion

In some patients, anatomical or technical difficulties may result in failure to achieve targeted result. Reports of such occurrences are now rare, with latest improvement in hardwares, but the available literature suggest an incidence of 4 to 6%.[1,2] Risk factors include lack of experience of the endovascular surgeon, lesion locations that are difficult to reach, and tortuous vasculature. When an endovascular procedure has to be abandoned, alternative methods include repeat angiography, open surgery, or radiotherapy. Careful study of the preoperative imaging, including noninvasive and invasive imaging of the access vessels and target lesion, is important in avoiding such situations. The use of postprocessing of images in three-dimensional (3D) software may help predict difficulties and thereby reduce the incidence of "failed" attempts. In the future, preoperative simulation of the anticipated procedure may not only prevent failed attempts but also allow preparation for the use of the specific devices most likely to succeed in a particular anatomical setting.[44]

## Hardware Failures

Older generation coils were used to stretch during coiling or sometimes detach before being deployed (►**Fig. 6**), so newer stretch resistant coils are introduced. Similarly microcatheter used to break in between during AVM embolization (►**Fig. 7**), so detachable microcatheters are available now to reduce complications. With the advancement in technologies, such hardware-related complications are decreasing but still they occur occasionally, and which as a neurointerventionist we have to deal more with presence of mind rather than on some facts and literature.

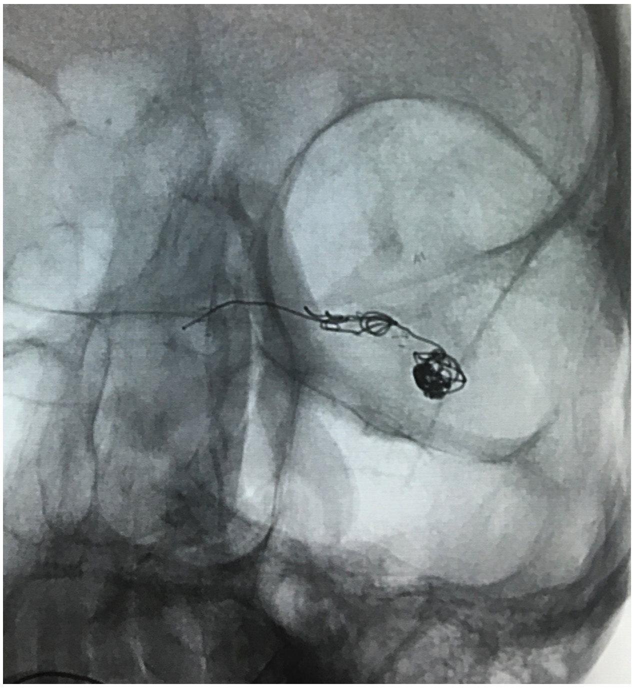

**Fig. 6** Early auto detachment of coil stent markers seen, which was used to hold coil in place.

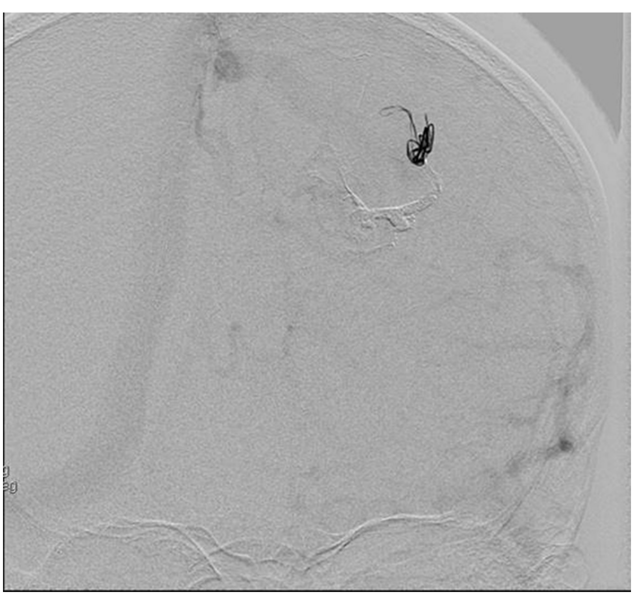

**Fig. 7** Broken and recoiled microcatheter during AVM embolization. Liquid embolization agent cast seen.

## Radiation-Induced Complications

This can be divided into acute and long-term effects. Short-term effects from ionizing radiation include skin burns that may occur from exposure to radiation doses as low as 2 Gy, whereas hair loss may occur after 3 Gy.[45] Not only is the patient at risk for harm due to ionizing radiation exposure during these procedures, but the treating physician is also at risk.[46] There are no prospective studies available in the literature that actually studies the cause and effect of relation of these radiations and neoplasms. Techniques to minimize radiation to both patients and their treating physicians include lead shielding, collimation, and minimizing the exposure time and number of runs during angiography.

## Conclusion

Endovascular neurosurgery has advanced rapidly since its inception over past few decades with evolving techniques and hardwares, thus reducing the incidence of complications. However, still whenever complications occur, significant morbidity and mortality are associated. A thorough knowledge of the procedures, hardwares, proper training, and knowledge about complication avoidance will help in reducing these adverse events. Also, experience, knowledge, and preparedness about the complications will help in managing these complications successfully, thus reducing morbidity.

### References


1 Ross IB, Dhillon GS. Complications of endovascular treatment of cerebral aneurysms. Surg Neurol 2005;64(1):12–18, discussion 18–19
2 Pierot L, Spelle L, Vitry F; ATENA Investigators. Immediate clinical outcome of patients harboring unruptured intracranial aneurysms treated by endovascular approach: results of the ATENA study. Stroke 2008;39(9):2497–2504
3 Wong JM, Ziewacz JE, Panchmatia JR, et al. Patterns in neurosurgical adverse events: endovascular neurosurgery. Neurosurg Focus 2012;33(5):E14 Review
4 Stone PA, Campbell JE. Complications related to femoral artery access for transcatheter procedures. Vasc Endovascular Surg 2012;46(8):617–623
5 Spies JB, Berlin L. Complications of femoral artery puncture. AJR Am J Roentgenol 1998;170(1):9–11
6 Bashir Q, Ishfaq A, Baig AA. Safety of diagnostic cerebral and spinal digital subtraction angiography in a developing country: a single-center experience. Interv Neurol 2018;7(1-2):99–109
7 Wagenbach A, Saladino A, Daugherty WP, Cloft HJ, Kallmes DF, Lanzino G. Safety of early ambulation after diagnostic and therapeutic neuroendovascular procedures without use of closure devices. Neurosurgery 2010;66(3):493–496, discussion 496–497
8 Rupp SB, Vogelzang RL, Nemcek AA Jr, Yungbluth MM. Relationship of the inguinal ligament to pelvic radiographic landmarks: anatomic correlation and its role in femoral arteriography. J Vasc Interv Radiol 1993;4(3):409–413
9 Altin RS, Flicker S, Naidech HJ. Pseudoaneurysm and arteriovenous fistula after femoral artery catheterization: association with low femoral punctures. AJR Am J Roentgenol 1989;152(3):629–631
10 Rapoport S, Sniderman KW, Morse SS, Proto MH, Ross GR. Pseudoaneurysm: a complication of faulty technique in femoral arterial puncture. Radiology 1985;154(2):529–530
11 Huggins CE, Gillespie MJ, Tan WA, et al. A prospective randomized clinical trial of the use of fluoroscopy in obtaining femoral arterial access. J Invasive Cardiol 2009;21(3):105–109
12 Abu-Fadel MS, Sparling JM, Zacharias SJ, et al. Fluoroscopy vs. traditional guided femoral arterial access and the use of closure devices: a randomized controlled trial. Catheter Cardiovasc Interv 2009;74(4):533–539
13 Dudeck O, Teichgraeber U, Podrabsky P, Lopez Haenninen E, Soerensen R, Ricke J. A randomized trial assessing the value of ultrasound-guided puncture of the femoral artery for interventional investigations. Int J Cardiovasc Imaging 2004;20(5):363–368

14 Cilingiroglu M, Feldman T, Salinger MH, Levisay J, Turi ZG. Fluoroscopically-guided micropuncture femoral artery access for large-caliber sheath insertion. J Invasive Cardiol 2011;23(4):157–161
15 Bhat FA, Changal KH, Raina H, Tramboo NA, Rather HA. Transradial versus transfemoral approach for coronary angiography and angioplasty - A prospective, randomized comparison. BMC Cardiovasc Disord 2017;17(1):23
16 Jones LE, Yang KH, Feldtman RW, et al. Safety and Efficacy of Arterial Closure Devices in an Office-Based Angiosuite. Ann Vasc Surg 2018;•••:S0890-5096(18)30270-X
17 Lata K, Kaki A, Grines C, Blank N, Elder M, Schreiber T. Pre-close technique of percutaneous closure for delayed hemostasis of large-bore femoral sheaths. J Interv Cardiol 2018
18 Karaolanis G, Kostakis ID, Moris D, Palla VV, Moulakakis KG. Fascia suture technique and suture-mediated closure devices: systematic review. Int J Angiol 2018;27(1):13–22
19 Pierot L, Rajpal G, Kadziolka K, Barbe C. The place for remodeling technique and stenting in the endovascular management of intracranial aneurysms: a single-center analysis from 2008 to 2010. Neuroradiology 2012;54(9):973–979
20 Cognard C, Weill A, Castaings L, Rey A, Moret J. Intracranial berry aneurysms: angiographic and clinical results after endovascular treatment. Radiology 1998;206(2):499–510
21 Song JK, Niimi Y, Fernandez PM, et al. Thrombus formation during intracranial aneurysm coil placement: treatment with intra-arterial abciximab. AJNR Am J Neuroradiol 2004;25(7):1147–1153
22 Mazighi M, Yadav JS, Abou-Chebl A. Durability of endovascular therapy for symptomatic intracranial atherosclerosis. Stroke 2008;39(6):1766–1769
23 Saatci I, Geyik S, Yavuz K, Cekirge HS. Endovascular treatment of brain arteriovenous malformations with prolonged intranidal Onyx injection technique: long-term results in 350 consecutive patients with completed endovascular treatment course. J Neurosurg 2011;115(1):78–88
24 Qureshi AI, Luft AR, Sharma M, Guterman LR, Hopkins LN. Prevention and treatment of thromboembolic and ischemic complications associated with endovascular procedures: Part II—clinical aspects and recommendations. Neurosurgery 2000;46(6):1360–1375, discussion 1375–1376
25 Fiehler J, Ries T. Prevention and treatment of thromboembolism during endovascular aneurysm therapy. Klin Neuroradiol 2009;19(1):73–81
26 Sedat J, Chau Y, Gaudart J, Sachet M, Beuil S, Lonjon M. Prasugrel versus clopidogrel in stent-assisted coil embolization of unruptured intracranial aneurysms. Interv Neuroradiol 2017;23(1):52–59
27 Yamada NK, Cross DT III, Pilgram TK, Moran CJ, Derdeyn CP, Dacey RG Jr. Effect of antiplatelet therapy on thromboembolic complications of elective coil embolization of cerebral aneurysms. AJNR Am J Neuroradiol 2007;28(9):1778–1782
28 Sedat J, Chau Y, Gaudard J, Suissa L, Lachaud S, Lonjon M. Administration of eptifibatide during endovascular treatment of ruptured cerebral aneurysms reduces the rate of thromboembolic events. Neuroradiology 2015;57(2):197–203
29 Bruening R, Mueller-Schunk S, Morhard D, et al. Intraprocedural thrombus formation during coil placement in ruptured intracranial aneurysms: treatment with systemic application of the glycoprotein IIb/IIIa antagonist tirofiban. AJNR Am J Neuroradiol 2006;27(6):1326–1331
30 Ries T, Buhk JH, Kucinski T, et al. Intravenous administration of acetylsalicylic acid during endovascular treatment of cerebral aneurysms reduces the rate of thromboembolic events. Stroke 2006;37(7):1816–1821
31 Morcos SK, Thomsen HS, Webb JA. Contrast-media-induced nephrotoxicity: a consensus report. Contrast Media Safety Committee, European Society of Urogenital Radiology (ESUR) Eur Radiol 1999;9(8):1602–1613
32 Lin J, Bonventre JV. Prevention of radiocontrast nephropathy. Curr Opin Nephrol Hypertens 2005;14(2):105–110
33 Kelly AM, Dwamena B, Cronin P, Bernstein SJ, Carlos RC. Meta-analysis: effectiveness of drugs for preventing contrast-induced nephropathy. Ann Intern Med 2008;148(4):284–294
34 Halliwell B, Gutteridge JM. Role of free radicals and catalytic metal ions in human disease: an overview. Methods Enzymol 1990;186:1–85
35 Drager LF, Andrade L, Barros de Toledo JF, Laurindo FR, Machado César LA, Seguro AC. Renal effects of N-acetylcysteine in patients at risk for contrast nephropathy: decrease in oxidant stress-mediated renal tubular injury. Nephrol Dial Transplant 2004;19(7):1803–1807
36 Zoungas S, Ninomiya T, Huxley R, et al. Systematic review: sodium bicarbonate treatment regimens for the prevention of contrast-induced nephropathy. Ann Intern Med 2009;151(9):631–638
37 Zagler A, Azadpour M, Mercado C, Hennekens CH. N-acetylcysteine and contrast-induced nephropathy: a meta-analysis of 13 randomized trials. Am Heart J 2006;151(1):140–145
38 Webb JG, Pate GE, Humphries KH, et al. A randomized controlled trial of intravenous N-acetylcysteine for the prevention of contrast-induced nephropathy after cardiac catheterization: lack of effect. Am Heart J 2004;148(3):422–429
39 Levy E, Koebbe CJ, Horowitz MB, et al. Rupture of intracranial aneurysms during endovascular coiling: management and outcomes. Neurosurgery 2001;49(4):807–811, discussion 811–813
40 Loh Y, Duckwiler GR; Onyx Trial Investigators. A prospective, multicenter, randomized trial of the Onyx liquid embolic system and N-butyl cyanoacrylate embolization of cerebral arteriovenous malformations. Clinical article. J Neurosurg 2010;113(4):733–741
41 Elijovich L, Higashida RT, Lawton MT, Duckwiler G, Giannotta S, Johnston SC; Cerebral Aneurysm Rerupture After Treatment (CARAT) Investigators. Predictors and outcomes of intraprocedural rupture in patients treated for ruptured intracranial aneurysms: the CARAT study. Stroke 2008;39(5):1501–1506
42 Park YK, Yi HJ, Choi KS, Lee YJ, Chun HJ. Intraprocedural Rupture During Endovascular Treatment of Intracranial Aneurysm: Clinical Results and Literature Review. World Neurosurg 2018;114:e605–e615
43 Weber W, Kis B, Siekmann R, Kuehne D. Endovascular treatment of intracranial arteriovenous malformations with onyx: technical aspects. AJNR Am J Neuroradiol 2007;28(2):371–377
44 Wong JM, Ziewacz JE, Panchmatia JR, et al. Patterns in neurosurgical adverse events: endovascular neurosurgery. Neurosurg Focus 2012;33(5):E14
45 Ketteler ER, Brown KR. Radiation exposure in endovascular procedures. J Vasc Surg 2011;53(1, Suppl):35S–38S
46 Valentin J. Avoidance of radiation injuries from medical interventional procedures. Ann ICRP 2000;30(2):7–67