Current Neurology and Neuroscience Reports (2019) 19: 6
https://doi.org/10.1007/s11910-019-0923-1

NEUROLOGY OF SYSTEMIC DISEASES (J BILLER, SECTION EDITOR)

Neurological Complications of Cardiological Interventions

Amir Shaban[1] · Enrique C. Leira[1,2,3]

Published online: 9 February 2019

Abstract

Purpose of Review Neurological complications are common during cardiac procedures. The type of procedure influences the profile of neurological complications and their management. In this article, we review the different neurological complications encountered following cardiac procedures, and treatment strategies for managing those complications.

Recent Findings Recent clinical trials have expanded the time window of eligibility for mechanical thrombectomy and intravenous thrombolysis. As a result, more options are now available for the treatment of periprocedural strokes.

Summary Early recognition of neurological complications, particularly stroke, will allow more patients to be treated effectively. The expanded window for intravenous thrombolysis and mechanical thrombectomy using advanced neuroimaging for selection provides more opportunities for treatment of periprocedural stroke. There is a paucity of data on the management of cerebrovascular complications, such as ischemic and hemorrhagic strokes, in the setting of left ventricular assist device or mechanical valve.

Keywords Cardiac procedure · Acute ischemic stroke · Intracranial hemorrhage · Nerve injury · Contrast neurotoxicity · Valve replacement · Coronary artery bypass grafting · Percutaneous coronary intervention · Left ventricular assist device

Introduction

Neurological complications following cardiac procedures significantly increase the morbidity and mortality. These complications range in severity from asymptomatic changes found incidentally on imaging to significantly disabling complications and death (Table 1). Neurological complications of cardiac procedures can involve both the central and peripheral nervous systems. It has been estimated that 6–28% of patients experience neurological complications following coronary bypass surgery [1]. The risk for neurological adverse events varies depending on the procedure itself and the premorbid condition. It is important to readily recognize those complications and provide appropriate management in a timely manner. The management of the same complication might differ following different procedures; for example, intravenous tissue plasminogen activator (IV-tPA) is likely contraindicated after a major heart surgery but may not be contraindicated following percutaneous coronary intervention (PCI). Mechanical thrombectomy, however, is not contraindicated after major surgeries.

In this article, we review the possible neurological complications following different cardiac procedure. We discuss their frequency, prevention, diagnosis, and treatment. These complications are summarized in (Table 2).

This article is part of the Topical Collection on *Neurology of Systemic Diseases*

✉ Amir Shaban
Amir-shaban@uiowa.edu

[1] Department of Neurology, Carver College of Medicine, University of Iowa, 200 Hawkins drive, Iowa City, IA 52242, USA

[2] Department of Neurosurgery, Carver College of Medicine, University of Iowa, Iowa City, IA, USA

[3] Department of Epidemiology, College of Public Health, University of Iowa, Iowa City, IA, USA

Acute Ischemic Stroke

Coronary Revascularization Procedures

Acute ischemic stroke is a known complication and a major cause of morbidity and mortality following cardiac revascularization procedures. Coronary artery bypass grafting (CABG) has higher rates of stroke (1–5%) in the short-term perioperative period compared to PCI (< 1%) [2–4]. However, PCI has higher rates of repeat revascularization which

Table 1 Neurological complications associated with cardiac procedure organized by system

Central nervous system	Peripheral nervous system injuries
Ischemic stroke, embolic, or hypoperfusion	Lumbosacral plexus
Hemorrhagic stroke	Femoral nerve
Spinal cord ischemia	Laryngeal nerve
Contrast-induced toxicity	Radial nerve
Transient cortical blindness	Ulnar nerve
Cognitive decline and dementia (controversial)	Median nerve

increases the long-term risk for stroke [2, 5•]. Stroke could either be embolic because of dislodging clots during vascular manipulations, or result from hypotension and hypoperfusion during the procedure.

Several factors are known to increase the risk for stroke following CABG: the complexity of the procedure itself, manipulation of the aorta, on-pump CABG, and perioperative onset of atrial fibrillation [3, 6]. Patient's premorbid factors can also increase the risk for stroke after CABG including older age, prior cardiac surgery, history of a prior stroke, poor ejection fraction, known carotid stenosis, and known peripheral vascular disease [3].

Table 2 Common neurological complications associated with each cardiac procedure and their management

Procedure	Complications	Management
Cardiac catheterization	Contrast-induced neurotoxicity	Supportive care
	Ischemic stroke	IV-tPA mechanical thrombectomy
	ICH	SBP < 140 Supportive care Surgical evacuation
	Lubosacral plexus and femoral nerve injury (femoral approach)	Supportive care
	Radial nerve injury (radial approach)	Supportive care
Arterial line placement	Radial nerve injury	Supportive care
CABG	Ischemic stroke	The benefit of IV-tPA should be weighed against the risk for bleeding into the surgical site Evaluate for mechanical thrombectomy
	ICH	SBP < 140
	RLN injury	Supportive for unilateral. May need respiratory support if bilateral
Valve replacement (TAVR and SAVR)	Early ischemic stroke	Discuss eligibility for IV-tPA with surgeon. Evaluate for mechanical thrombectomy
	ICH due to anticoagulation and antiplatelet use	SBP < 140 Considered reversing anticoagulation in the acute settings. The duration of anticoagulation withholding is decided on case by case basis, usually between 3 days and 10 weeks
LVAD	Ischemic stroke	Continue anticoagulation
	ICH	SBP < 140 Considered reversing anticoagulation in the acute settings. The duration of anticoagulation withholding is decided on case by case basis
Aortic aneurysm repair	Spinal cord ischemia	Consider CSF drain for prevention
Coarctation of aorta repair	Spinal cord ischemia	Consider CSF drain for prevention
Cardioversion	Dislodging a clot from the atrium	Evaluate for IV-tPA and mechanical thrombectomy
	Recurrence of atrial fibrillation	
TEE	Ischemic stroke	Evaluate for IV-tPA and mechanical thrombectomy
	RLN injury	Supportive for unilateral. May need respiratory support if bilateral

ICH intracerebral hemorrhage

The risk for stroke following PCI is also affected by the complexity of the cardiac lesion and procedural aspects (such as guidewire caliber, multiple catheter exchanges, and the use of intra-aortic balloon pump). The risk for stroke is also higher in patients who are hemodynamically unstable or have higher pre-procedural stroke risk factors [3].

Aspirin and clopidogrel treatment prior to the procedure lowers the risk for periprocedural stroke [7, 8]. Several perioperative neuroprotection techniques have been tried including mild hypothermia, embolic protection devices, cerebral ischemic preconditioning, erythropoietin administration, and intraoperative transesophageal echocardiogram (TEE) to identify aortic atheroma, the results of which have been controversial and require further investigation.

Valvular Procedures

Periprocedural ischemic stroke is a known complication following valve replacement procedures. The risk varies based on the procedure and type of valve chosen. Radiological subclinical strokes have been detected in most patients following transcatheter aortic valve replacement (TAVR) [9]. The overall incidence of symptomatic ischemic stroke or TIA at 30 days following TAVR procedure is 3.3% ± 1.8% [10]. Endovascular manipulations such as performing balloon aortic valvuloplasty, crossing a severely calcified aortic valve, position of the rigid device across the native valve, and deployment of the prosthetic valve further increase the risk for stroke [11]. However, a large meta-analysis showed no significant difference in 30-day risk for stroke between the SAPIEN valve 3% and the CoreValve 2.4% [12]. There was no difference in stroke incidence between transfemoral and transapical approaches [12]. Higher incidence of embolic strokes has been reported with TAVR procedure compared to surgical and non-operative control groups [13]. Ischemic stroke rates are higher in the acute periprocedural phase and subside thereafter. Procedural factors explain very early strokes presenting within 24 h, whereas arrhythmias explain the rest of the stroke during the acute phase [14].

Several embolic protection devices have been used during TAVR procedures. Many of those devices have proven safe in clinical trials [15]. A meta-analysis showed that embolic protection devices were associated with smaller volume of silent strokes but did not reduce the number of clinical events or mortality [15].

Following TAVR, dual antiplatelet therapy with aspirin and clopidogrel for 3–6 months is currently used for ischemic stroke prevention [11, 16]. However, one meta-analysis showed that dual antiplatelet therapy was not associated with lower 30-day stroke rates and resulted in higher rates of bleeding (17% vs 7%, $P = 0.0006$) compared to single antiplatelet therapy [17].

Surgical valve replacement has been associated with 1.5% risk for stroke. A prospective study reported up to 17% incidence of stroke detected by a neurologist following surgical aortic valve replacement [18]. Risk factors associated with higher rates of ischemic stroke included older age, prior strokes, emergent (non-elective) surgery, high blood transfusion requirements, longer cardiopulmonary bypass times, and the use of hemofiltration [19].

Ischemic stroke prevention following surgical valve replacement depends on the valve type (Fig. 1). Anticoagulation with warfarin for the first 3 months followed by aspirin thereafter is recommended following bioprosthetic valve surgical replacement [16]. Mechanical valves are more durable and used for patients with long life expectancy; however, they are thrombogenic and require lifelong anticoagulation therapy. Warfarin therapy decreases the rates of thromboembolic events to 1 per 100 patient-years [20]. Current guidelines recommend a target INR of 2.5 in addition to aspirin for aortic mechanical valves with no additional thromboembolic risk factors. Mitral valve requires an INR goal of 3 in addition to aspirin [16]. Several factors affect the risk for stroke following mechanical valve placement including valve design, valve location, association with atrial fibrillation, cardiac ejection fraction, age, left atrial diameter, and associated mitral stenosis [20].

Cardioversion

Cardioversion is sometimes used for converting atrial fibrillation into sinus rhythm. The risk for periprocedural cardioembolic events has been reported to be as high as 7% without using anticoagulation and 0.8% with the use of anticoagulation prior to the procedure [21]. The risk for recurrent Afib after initial cardioversion is about 32% [22]. Several mechanisms have been described for ischemic stroke following cardioversion including preexisting left atrial thrombus dislodgement, activation of inflammatory responses, and the presence of structural abnormalities in the atrium [23]. Transesophageal echocardiography (TEE) can be used to rule out preexisting left atrial thrombus but is not routinely used unless cardioversion is needed urgently without adequate anticoagulation. TEE itself can rarely dislodge a clot and cause acute ischemic stroke [24].

LVAD

Ischemic stroke is the most serious complication of left ventricular assist device (LVAD) and a major contributor to morbidity and mortality. Continuous flow devices are currently the most common ventricular assist devices used in the USA [25]. The risk for ischemic stroke following LVAD placement ranges from 6 to 18% [25, 26]. The thrombogenicity of LVAD may be related to the artificial surfaces and the

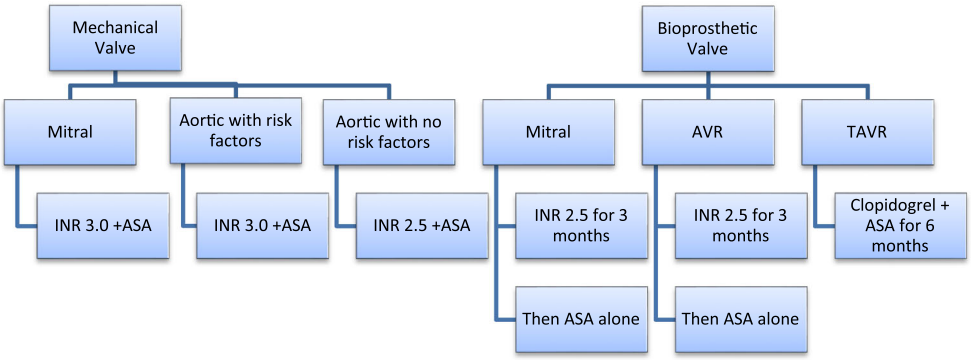

Fig. 1 Guidelines for antithrombotic management for ischemic stroke prevention following valve replacement

higher blood shear forces inside LVADs, which could lead to the activation of the coagulation and fibrinolytic systems [27]. Anticoagulation is typically used to prevent LVAD thrombosis and to decrease the risk for ischemic stroke.

Management of an ischemic stroke occurring in the setting of LVAD is challenging. Despite the increased risk for hemorrhagic transformation, anticoagulation is commonly continued in the acute stroke period to prevent further LVAD thrombosis and embolization.

Management of Acute Ischemic Stroke Following Cardiac Procedures

After stabilizing the patient, the first step in managing acute ischemic stroke is determining the last known well time. Intravenous thrombolysis is recommended within 4.5 h from last known well. Often, symptoms are discovered after the procedure when the anesthesia effect subsides. For those patients, last known well time is the time of the anesthesia induction. Unfortunately, many of these patients will be outside the treatment window for standard IV-tPA treatment.

These patients might still benefit from advanced neuroimaging to determine eligibility for IV-tPA. Recent clinical trial investigated the use of IV-tPA guided by a mismatch between diffusion-weighted imaging and FLAIR in the region of ischemia in patients with unclear last known well. It showed better functional outcomes with IV-tPA despite a relative increase in intracranial hemorrhages than placebo [28••].

CABG is a major surgical procedure and typically considered a contraindication for IV-tPA due to the concern for bleeding into the surgical site. The risk for bleeding into the surgical site should be weighed against the severity of the stroke and the potential for disability. We recommend estimating the risk for bleeding for every individual patient with the surgeon who performed the procedure. Recent MI (including STEMI and NSTEMI) is a relative contraindication for IV-tPA [29]. Periprocedural anticoagulation is considered a contraindication for IV-tPA [29]. On the other hand, mechanical thrombectomy is not contraindicated after cardiac surgery and is an option in case of a large vessel occlusion.

Patients with mechanical valves are often on warfarin. INR > 1.7 remains an absolute contraindication for IV-tPA [29]. We do not recommend reversing the INR in the setting of ischemic stroke to qualify for IV-tPA. Dual antiplatelet use, however, is not a contraindication for IV-tPA.

Even though many of post-cardiac procedure patients may not be eligible for IV-tPA due to presenting outside the treatment window or the presence of the contraindications described above, some of them can be eligible for mechanical thrombectomy. Patients with suspected large vessel occlusion strokes should be evaluated for mechanical thrombectomy. The time window for thrombectomy has been recently extended to 24 h for patients who meet certain clinical and radiographic criteria [30••, 31••].

Hemorrhagic Stroke

The risk for intracranial hemorrhage (ICH) following CABG is lower (< 0.5%) than the risk for ischemic stroke. The ICH could be related to the periprocedural use of heparin [32]. Renal dysfunction can further increase the risk for ICH following CABG [32].

Valvular replacement procedures are associated with increased risk for thromboembolism. Patients are placed on dual antiplatelet therapy for 3–6 months following TAVR or on anticoagulation following surgical replacement. Mechanical valve placement requires lifelong anticoagulation. While the risk for ischemic events is higher in the acute phase following the valve replacement, the risk for hemorrhagic events increases in the late phase following valve replacement and is related to anticoagulation and antiplatelet therapy. Dual antiplatelet therapy for bioprosthetic valves provides better prevention of ischemic events compared with single antiplatelet therapy but is associated with higher risk for ICH. Anticoagulation for mechanical valves increases the risk for hemorrhagic strokes; this risk is increased with higher INR goal [33]. Figure 1 summarizes the recommendations for thromboembolic prevention following valvular procedures.

Continuous anticoagulation is needed for LVAD patients to help prevent device thrombosis. Besides, acquired von

Willebrand disease has been associated with LVAD which further increases the risk for ICH [34]. As a result, 8–11% of patients with LVAD suffer from ICH [35]. High mortality rates (> 50%) have been reported in patients who developed ICH in the setting of LVAD.

Management of ICH in the Setting of Mechanical Valves or LVAD

Management of this neurological emergency starts with stabilizing the patient, including securing the airway which may require endotracheal intubation in cases with severely decreased level of consciousness. The systolic blood pressure should be maintained below 140 mmHg in the acute phase following the hemorrhage [36]. A CT scan of the brain should be obtained as soon as possible, and a hemorrhage severity score (ICH score) should be performed as a part of the initial evaluation [36]. Consider obtaining contrast-enhanced imaging if underlying vascular malformation is suspected and to evaluate for sign of active bleeding (the spot sign) [36]. Consider repeating non-contrasted CT scan in 6 h to evaluate for hemorrhage expansion. It is unlikely for an ICH to cause a drop in the hemoglobin so that occurrence should trigger investigation into a second source of bleeding.

Management of the anticoagulation could be challenging. In the absence of clinical trials, the decision regarding anticoagulation reversal and/or timing for restarting anticoagulation should be determined on a case-by-case basis depending on the severity of the hemorrhage and the risk for device thrombosis.

In general, rapid reversal of INR to < 1.4 is recommended in the acute setting of warfarin-related hemorrhage [36, 37]. Achieving adequate reversal of INR within 4 h of admission was associated with lower rates of hematoma expansion [37].

The optimal time for resumption of anticoagulation is uncertain and depends on the estimated risk for thromboembolism. Restarting anticoagulation within 2–10 weeks following the initial ICH was associated with increased risk for hemorrhage expansion [36, 38, 39]. However, this risk for ICH should be weighed against the risk for thromboembolism and mechanical valve thrombosis. The European Society of Cardiology Working Group on Thrombosis suggested in their consensus statement that heparin may be safely restarted 3 days following ICH and switched to warfarin on day 7 [40]. This recommendation was based on observational studies. In a pooled analysis of 2504 patients, the risk for hemorrhage significantly outweighed the benefit when anticoagulation was started within the first 6 days following ICH; as a result, authors recommended against starting anticoagulation during that period [39].

Limited data is available to guide anticoagulation management following ICH in the setting of LVAD. Patients often undergo reversal of anticoagulation in the acute settings with data from case series showing no increase in the thrombotic events [41, 42]. In two case series studies, patients with smaller ICH were successfully managed without reversal (mean ICH volume 0.4 cc and 19 cc) [41, 42].

An observational study of 36 patients recommended withholding anticoagulation for 10 days following ICH in the setting of LVAD [43]. In our practice, we assess the risks and benefits of reversing and withholding anticoagulation following ICH in the setting of LVAD on a case-by-case basis by factoring the size of the hemorrhage, location, and the severity of the clinical symptoms.

Spinal Cord Ischemia

Spinal cord infarction is a known complication of aortic aneurysm and coarctation of aorta repair surgeries. Spinal cord ischemia occurs in 0.2% of cases undergoing endovascular abdominal aortic aneurysmal repair (EVAR) [44].

The symptoms depend on the affected spinal vascular territory. The most common territory involved is the anterior spinal artery. The onset is sudden or rapidly progressive over minutes or hours, and can include radicular acute pain from ischemia in the nerve roots. Most commonly, patients wake up from anesthesia with established symptoms of bilateral paralysis, bowel and bladder dysfunction, loss of temperature, and pain sensation with preserved vibration sensation. Sometimes, only part of those symptoms is present. Technical difficulties during the EVAR procedure itself have been associated with higher risk for spinal cord ischemia [44]. A CSF drainage device and steroids have been suggested for the prevention of spinal cord ischemia [44, 45]. Intraoperative somatosensory evoked potential (SSEP) monitoring is also used to detect cord ischemia early during the surgery [46].

Cognitive Decline and Dementia

The risk for cognitive decline following CABG procedure remains controversial. In one study, 41% of patients had worse performance on their neuropsychological testing 5 years after CABG compared to their performance at baseline [47]. It was suspected that the use of cardiopulmonary bypass was the cause of the cognitive decline and was sometimes referred to as “pump-head.” However, subsequent studies have not replicated those findings and found similar degrees of cognitive declines in patients who underwent CABG when compared to patient who had medical management [48]. Furthermore, cognitive decline rates have been similar in patients after on-pump CABG and those after off-pump surgeries [49, 50]. It appears that the risk for cognitive decline following CABG is closely related to the cardiac disease itself rather than the surgery. Many candidates for CABG were found to have cerebral infarction on MRI prior to any surgeries which might be related to the subsequent cognitive decline [51]. Thus,

cerebrovascular risk modification may play and important role in minimizing the risk for cognitive decline following cardiac procedures. Multiple studies failed to show any benefit for using hypothermia to prevent cognitive decline during the cardiac surgery [52, 53].

Interestingly, valve replacement procedures such as TAVR have shown preservation or improvement in the cognitive function [54, 55].

Contrast-Induced Neurotoxicity

Contrast-induced neurotoxicity (CIN) is a rare complication associated with the use of iodine contrast for cardiac catheterization. This complication is less common than ischemic and hemorrhagic strokes, with the reported incidence of 1–2% of all patients [56–58]. The pathophysiology is not completely understood but is thought to be related to blood-brain barrier disruption, increased permeability, and cerebral autoregulation dysfunction [56].

Clinical presentation is variable including headache, seizures, diplopia, encephalopathy, and rarely coma. Transient cortical blindness is a unique presentation and is separately described below. In most patients, symptoms completely resolve within days [56].

Imaging studies are mainly obtained to rule out more common causes of symptoms such as ischemic and hemorrhagic strokes. Initial MRI and CT are commonly unremarkable but can reveal contrast leak in the cortex or the subarachnoid space, and cerebral edema especially in the vertebrobasilar territory which is more prone to disturbances of autoregulation [56].

Renal failure and hypertension have been associated with contrast-induced neurotoxicity [56, 59]. There has been no clear association with the amount of contrast used, rate of infusion, or duration of the endovascular procedure [56, 59]. Management includes hypertension control and close monitoring. Some authors reported using corticosteroids, hydration, mannitol, and antiplatelet therapy without adverse events [56, 59].

Transient Cortical Blindness

Reported in 0.01–1.0% of patients following cardiac and non-cardiac endovascular procedures [60], the pathophysiology is thought to be similar to that of contrast-induced encephalopathy (described above) [60, 61]. The blindness is self-limiting and resolves spontaneously in hours or days; thus, diagnosis of transient cortical blindness can only be made retrospectively after the resolution of the blindness. Examination reveals bilateral vision loss with intact retinal examination and intact pupillary light reflex. It is crucial to exclude ischemic and hemorrhagic cerebral complications, as these have different management. MRI and CT imaging can reveal bilateral edema especially in the posterior circulation territories and contrast in the cerebral parenchyma or the subarachnoid space [60].

Peripheral Nerve Injury

Radial Nerve Injury

This is a rare complication and could result from arterial line placement for blood pressure monitoring or transradial approach catheterization. This complication could result from either direct nerve injury, pressure from a hematoma, or compartment syndrome [62, 63].

Median Nerve Injury

Median nerve could be injured in the antecubital fossa following brachial artery catheterization by direct nerve injury or due to compression by a hematoma.

Patient with history of carpal tunnel syndrome could have worsening of symptoms following arterial line placement, whereas developing de novo symptoms of carpal tunnel syndrome is very rare following line placement [64].

Lumbosacral Plexus and Femoral Nerve Injuries

These injuries are associated with procedures that use femoral access for cardiac, cerebrovascular, and peripheral vascular procedures. The risk of femoral neuropathy following transfemoral access is very low 4–200 in 100,000 patients [65, 66]. Sensory deficits are more common than motor deficits [66].

The presenting symptoms will vary depending on the nerves involved. The femoral nerve (weakness of quadriceps and psoas) is most commonly injured, but other nerves could be involved including lateral femoral cutaneous (numbness in the lateral thigh) and obturator (weakness in thigh adductors).

The most common mechanism of injury is due to pressure from a retroperitoneal hematoma. Retroperitoneal hematomas have been reported in 0.5% of patients undergoing femoral artery catheterization [67]. Several risk factors have been associated with higher rates of hematoma following femoral puncture: multiple procedures, large-caliber vascular sheaths, high femoral puncture, low body surface area, obesity, advanced age, peripheral vascular disease, chronic renal insufficiency, thrombocytopenia, and excessive anticoagulation [67].

Less commonly, the formation of femoral artery pseudoaneurysm can also result in pressure on the nearby femoral nerve. Digital pressure application can also cause direct injury to the femoral nerve.

Diagnosis of this condition requires high level of suspicion. Clinical presentation may include pelvic or thigh

pain, declining hemoglobin and hematocrit values, tachycardia, and arterial hypotension. If hematoma is suspected, abdominal and pelvic imaging should be obtained to visualize the hematoma. There is no role for EMG in the acute settings but could be helpful if symptoms persisted.

Treatment remains controversial. Conservative management has been used for mild cases of femoral nerve compression. Acute and severe compression may warrant surgical decompression.

RLN Injury

Recurrent laryngeal nerve (RLN) injury is a known complication of cardiac surgeries (including CABG) with incidence rate of 1% [68]. The injury may result from surgical dissection, topical ice slush, or during traction [68]. This complication has also been reported following a TEE.

Anatomically, the left RLN is longer and more prone to injury. It arises from the vagus at aortic arch in the thorax. Conversely, the right RLN arises from the vagus at the subclavian artery. Both RLNs ascend on the sides of the esophagus. Unilateral injury is more common. Although bilateral injuries are rare, they can be life threatening. Bilateral RLN injury can cause respiratory compromise and may occur following bilateral internal thoracic artery harvesting [68].

Conclusions

Neurological complications following cardiac procedures are common. They can involve the central and peripheral nervous systems. They significantly increase morbidity, mortality, and length of stay. Ischemic stroke is the most common neurological complication following cardiac procedures, and the management is challenging. Standard intravenous thrombolysis may be contraindicated, but imaging-guided thrombolysis and mechanical thrombectomy might be options. The need and management of anticoagulation in the setting of ischemic and hemorrhagic strokes can be problematic.

Compliance with Ethical Standards

Conflict of Interest Amir Shaban and Enrique Leira each declare no potential conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Gottesman RF, McKhann GM, Hogue CW. Neurological complications of cardiac surgery. Semin Neurol. 2008;28(5):703–15.
2. Shah R, Morsy MS, Weiman DS, Vetrovec GW. Meta-analysis comparing coronary artery bypass grafting to drug-eluting stents and to medical therapy alone for left main coronary artery disease. Am J Cardiol. 2017;120(1):63–8.
3. Devgun JK, Gul S, Mohananey D, Jones BM, Hussain MS, Jobanputra Y, et al. Cerebrovascular events after cardiovascular procedures: risk factors, recognition, and prevention strategies. J Am Coll Cardiol. 2018;71(17):1910–20.
4. Stone GW, Sabik JF, Serruys PW, Kappetein AP. Everolimus-eluting stents or bypass surgery for left main coronary disease. N Engl J Med. 2017;376(11):1089.
5. • Serruys PW, Morice MC, Kappetein AP, Colombo A, Holmes DR, Mack MJ, et al. Percutaneous coronary intervention versus coronary-artery bypass grafting for severe coronary artery disease. N Engl J Med. 2009;360(10):961–72 **SYNTAX trial was one of the major trials to compare the adverse events following coronary artery bypass grafting and percutaneous coronary intervention.**
6. Kowalewski M, Pawliszak W, Malvindi PG, Bokszanski MP, Perlinski D, Raffa GM, et al. Off-pump coronary artery bypass grafting improves short-term outcomes in high-risk patients compared with on-pump coronary artery bypass grafting: meta-analysis. J Thorac Cardiovasc Surg. 2016;151(1):60–77 e1–58.
7. Kenaan M, Seth M, Aronow HD, Wohns D, Share D, Gurm HS, et al. The clinical outcomes of percutaneous coronary intervention performed without pre-procedural aspirin. J Am Coll Cardiol. 2013;62(22):2083–9.
8. Aradi D, Komocsi A, Vorobcsuk A, Serebruany VL. Impact of clopidogrel and potent P2Y 12 -inhibitors on mortality and stroke in patients with acute coronary syndrome or undergoing percutaneous coronary intervention: a systematic review and meta-analysis. Thromb Haemost. 2013;109(1):93–101.
9. Kahlert P, Knipp SC, Schlamann M, Thielmann M, Al-Rashid F, Weber M, et al. Silent and apparent cerebral ischemia after percutaneous transfemoral aortic valve implantation: a diffusion-weighted magnetic resonance imaging study. Circulation. 2010;121(7):870–8.
10. Eggebrecht H, Schmermund A, Voigtlander T, Kahlert P, Erbel R, Mehta RH. Risk of stroke after transcatheter aortic valve implantation (TAVI): a meta-analysis of 10,037 published patients. EuroIntervention. 2012;8(1):129–38.
11. Hahn RT, Pibarot P, Webb J, Rodes-Cabau J, Herrmann HC, Williams M, et al. Outcomes with post-dilation following transcatheter aortic valve replacement: the PARTNER I trial (placement of aortic transcatheter valve). JACC Cardiovasc Interv. 2014;7(7):781–9.
12. Athappan G, Gajulapalli RD, Sengodan P, Bhardwaj A, Ellis SG, Svensson L, et al. Influence of transcatheter aortic valve replacement strategy and valve design on stroke after transcatheter aortic valve replacement: a meta-analysis and systematic review of literature. J Am Coll Cardiol. 2014;63(20):2101–10.
13. Jones BM, Tuzcu EM, Krishnaswamy A, Kapadia SR. Neurologic events after transcatheter aortic valve replacement. Interv Cardiol Clin. 2015;4(1):83–93.

14. Nombela-Franco L, Webb JG, de Jaegere PP, Toggweiler S, Nuis RJ, Dager AE, et al. Timing, predictive factors, and prognostic value of cerebrovascular events in a large cohort of patients undergoing transcatheter aortic valve implantation. Circulation. 2012;126(25):3041–53.
15. Bagur R, Solo K, Alghofaili S, Nombela-Franco L, Kwok CS, Hayman S, et al. Cerebral embolic protection devices during transcatheter aortic valve implantation: systematic review and meta-analysis. Stroke. 2017;48(5):1306–15.
16. Nishimura RA, Otto CM, Bonow RO, Carabello BA, Erwin JP 3rd, Guyton RA, et al. 2014 AHA/ACC guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. J Am Coll Cardiol. 2014;63(22):2438–88.
17. Aryal MR, Karmacharya P, Pandit A, Hakim F, Pathak R, Mainali NR, et al. Dual versus single antiplatelet therapy in patients undergoinHeart Lung Circg transcatheter aortic valve replacement: a systematic review and meta-analysis. 2015;24(2):185–92.
18. Messe SR, Acker MA, Kasner SE, Fanning M, Giovannetti T, Ratcliffe SJ, et al. Stroke after aortic valve surgery: results from a prospective cohort. Circulation. 2014;129(22):2253–61.
19. Hauville C, Ben-Dor I, Lindsay J, Pichard AD, Waksman R. Clinical and silent stroke following aortic valve surgery and transcatheter aortic valve implantation. Cardiovasc Revasc Med. 2012;13(2):133–40.
20. Baber U, van der Zee S, Fuster V. Anticoagulation for mechanical heart valves in patients with and without atrial fibrillation. Curr Cardiol Rep. 2010;12(2):133–9.
21. Arnold AZ, Mick MJ, Mazurek RP, Loop FD, Trohman RG. Role of prophylactic anticoagulation for direct current cardioversion in patients with atrial fibrillation or atrial flutter. J Am Coll Cardiol. 1992;19(4):851–5.
22. Hellman T, Kiviniemi T, Vasankari T, Nuotio I, Biancari F, Bah A, et al. Prediction of ineffective elective cardioversion of atrial fibrillation: a retrospective multi-center patient cohort study. BMC Cardiovasc Disord. 2017;17(1):33.
23. Jaakkola S, Kiviniemi TO, Airaksinen KEJ. Cardioversion for atrial fibrillation—how to prevent thromboembolic complications? Ann Med. 2018:1–7.
24. Cote G, Denault A. Transesophageal echocardiography-related complications. Can J Anaesth. 2008;55(9):622–47.
25. Kislitsina ON, Anderson AS, Rich JD, Vorovich EE, Pham DT, Cox JL, et al. Strokes associated with left ventricular assist devices. J Card Surg. 2018;33(9):578–83.
26. Cho SM, Moazami N, Frontera JA. Stroke and intracranial hemorrhage in HeartMate II and HeartWare left ventricular assist devices: a systematic review. Neurocrit Care. 2017;27(1):17–25.
27. Blitz A. Pump thrombosis—a riddle wrapped in a mystery inside an enigma. Ann Cardiothorac Surg. 2014;3(5):450–71.
28.•• Thomalla G, Simonsen CZ, Boutitie F, Andersen G, Berthezene Y, Cheng B, et al. MRI-guided thrombolysis for stroke with unknown time of onset. N Engl J Med. 2018;379(7):611–22 **WAKE-UP trial investigated the use of IV-tPA guided by a mismatch between diffusion weighted imaging and FLAIR in the region of ischemia and showed a significantly better functional outcome compared to placebo.**
29. Powers WJ, Rabinstein AA, Ackerson T, Adeoye OM, Bambakidis NC, Becker K, et al. 2018 guidelines for the early management of patients with acute ischemic stroke: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2018;49(3):e46–e110.
30.•• Nogueira RG, Jadhav AP, Haussen DC, Bonafe A, Budzik RF, Bhuva P, et al. Thrombectomy 6 to 24 hours after stroke with a mismatch between deficit and infarct. N Engl J Med. 2018;378(1):11–21 **DAWN trial showed a significant benefit for using of mechanical thrombectomy for patients who met specific criteria up to 24 hours.**
31.•• Albers GW, Marks MP, Kemp S, Christensen S, Tsai JP, Ortega-Gutierrez S, et al. Thrombectomy for stroke at 6 to 16 hours with selection by perfusion imaging. N Engl J Med. 2018;378(8):708–18 **DEFUSE trial showed a significant benefit for using of mechanical thrombectomy for patients who met specific criteria up to 16 hours.**
32. Holzmann MJ, Ahlback E, Jeppsson A, Sartipy U. Renal dysfunction and long-term risk of ischemic and hemorrhagic stroke following coronary artery bypass grafting. Int J Cardiol. 2013;168(2):1137–42.
33. Stewart RA. Clinical trials in heart valve disease. Curr Opin Cardiol. 2009;24(4):279–87.
34. Suarez J, Patel CB, Felker GM, Becker R, Hernandez AF, Rogers JG. Mechanisms of bleeding and approach to patients with axial-flow left ventricular assist devices. Circ Heart Fail. 2011;4(6):779–84.
35. Slaughter MS, Rogers JG, Milano CA, Russell SD, Conte JV, Feldman D, et al. Advanced heart failure treated with continuous-flow left ventricular assist device. N Engl J Med. 2009;361(23):2241–51.
36. Hemphill JC 3rd, Greenberg SM, Anderson CS, Becker K, Bendok BR, Cushman M, et al. Guidelines for the management of spontaneous intracerebral hemorrhage: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2015;46(7):2032–60.
37. Kuramatsu JB, Gerner ST, Schellinger PD, Glahn J, Endres M, Sobesky J, et al. Anticoagulant reversal, blood pressure levels, and anticoagulant resumption in patients with anticoagulation-related intracerebral hemorrhage. JAMA. 2015;313(8):824–36.
38. Majeed A, Kim YK, Roberts RS, Holmstrom M, Schulman S. Optimal timing of resumption of warfarin after intracranial hemorrhage. Stroke. 2010;41(12):2860–6.
39. Kuramatsu JB, Sembill JA, Gerner ST, Sprugel MI, Hagen M, Roeder SS, et al. Management of therapeutic anticoagulation in patients with intracerebral haemorrhage and mechanical heart valves. Eur Heart J. 2018;39(19):1709–23.
40. Halvorsen S, Storey RF, Rocca B, Sibbing D, Ten Berg J, Grove EL, et al. Management of antithrombotic therapy after bleeding in patients with coronary artery disease and/or atrial fibrillation: expert consensus paper of the European Society of Cardiology Working Group on thrombosis. Eur Heart J. 2017;38(19):1455–62.
41. Tahir RA, Rotman LE, Davis MC, Dupepe EB, Kole MK, Rahman M, et al. Intracranial hemorrhage in patients with a left ventricular assist device. World Neurosurg. 2018;113:e714–e21.
42. Wong JK, Chen PC, Falvey J, Melvin AL, Lidder AK, Lowenstein LM, et al. Anticoagulation reversal strategies for left ventricular assist device patients presenting with acute intracranial hemorrhage. ASAIO J. 2016;62(5):552–7.
43. Wilson TJ, Stetler WR Jr, Al-Holou WN, Sullivan SE, Fletcher JJ. Management of intracranial hemorrhage in patients with left ventricular assist devices. J Neurosurg. 2013;118(5):1063–8.
44. Moulakakis KG, Alexiou VG, Karaolanis G, Sfyroeras GS, Theocharopoulos GN, Lazaris AM, et al. Spinal cord ischemia following elective endovascular repair of Infrarenal aortic aneurysms: a systematic review. Ann Vasc Surg. 2018;52:280–91.
45. Miyamoto K, Ueno A, Wada T, Kimoto S. A new and simple method of preventing spinal cord damage following temporary occlusion of the thoracic aorta by draining the cerebrospinal fluid. J Cardiovasc Surg. 1960;1:188–97.
46. Cunningham JN Jr, Laschinger JC, Merkin HA, Nathan IM, Colvin S, Ransohoff J, et al. Measurement of spinal cord ischemia during operations upon the thoracic aorta: initial clinical experience. Ann Surg. 1982;196(3):285–96.

47. Newman MF, Kirchner JL, Phillips-Bute B, Gaver V, Grocott H, Jones RH, et al. Longitudinal assessment of neurocognitive function after coronary-artery bypass surgery. N Engl J Med. 2001;344(6):395–402.
48. Selnes OA, Gottesman RF, Grega MA, Baumgartner WA, Zeger SL, McKhann GM. Cognitive and neurologic outcomes after coronary-artery bypass surgery. N Engl J Med. 2012;366(3):250–7.
49. Stroobant N, van Nooten G, De Bacquer D, Van Belleghem Y, Vingerhoets G. Neuropsychological functioning 3-5 years after coronary artery bypass grafting: does the pump make a difference? Eur J Cardiothorac Surg. 2008;34(2):396–401.
50. Kennedy ED, Choy KC, Alston RP, Chen S, Farhan-Alanie MM, Anderson J, et al. Cognitive outcome after on- and off-pump coronary artery bypass grafting surgery: a systematic review and meta-analysis. J Cardiothorac Vasc Anesth. 2013;27(2):253–65.
51. Goto T, Baba T, Honma K, Shibata Y, Arai Y, Uozumi H, et al. Magnetic resonance imaging findings and postoperative neurologic dysfunction in elderly patients undergoing coronary artery bypass grafting. Ann Thorac Surg. 2001;72(1):137–42.
52. Boodhwani M, Rubens F, Wozny D, Rodriguez R, Nathan HJ. Effects of sustained mild hypothermia on neurocognitive function after coronary artery bypass surgery: a randomized, double-blind study. J Thorac Cardiovasc Surg. 2007;134(6):1443–50 discussion 51-2.
53. Nathan HJ, Rodriguez R, Wozny D, Dupuis JY, Rubens FD, Bryson GL, et al. Neuroprotective effect of mild hypothermia in patients undergoing coronary artery surgery with cardiopulmonary bypass: five-year follow-up of a randomized trial. J Thorac Cardiovasc Surg. 2007;133(5):1206–11.
54. Lai KS, Herrmann N, Saleem M, Lanctot KL. Cognitive outcomes following transcatheter aortic valve implantation: a systematic review. Cardiovasc Psychiatry Neurol. 2015;2015:209569.
55. Liimatainen J, Perakyla J, Jarvela K, Sisto T, Yli-Hankala A, Hartikainen KM. Improved cognitive flexibility after aortic valve replacement surgery. Interact Cardiovasc Thorac Surg. 2016;23(4):630–6.
56. Kocabay G, Karabay CY, Kalayci A, Akgun T, Guler A, Oduncu V, et al. Contrast-induced neurotoxicity after coronary angiography. Herz. 2014;39(4):522–7.
57. Leong S, Fanning NF. Persistent neurological deficit from iodinated contrast encephalopathy following intracranial aneurysm coiling. A case report and review of the literature. Interv Neuroradiol. 2012;18(1):33–41.
58. Guimaraens L, Vivas E, Fonnegra A, Sola T, Soler L, Balaguer E, et al. Transient encephalopathy from angiographic contrast: a rare complication in neurointerventional procedures. Cardiovasc Intervent Radiol. 2010;33(2):383–8.
59. Tong X, Hu P, Hong T, Li M, Zhang P, Li G, et al. Transient cortical blindness associated with endovascular procedures for intracranial aneurysms. World Neurosurg. 2018;119:123–31.
60. Zwicker JC, Sila CA. MRI findings in a case of transient cortical blindness after cardiac catheterization. Catheter Cardiovasc Interv. 2002;57(1):47–9.
61. Lantos G. Cortical blindness due to osmotic disruption of the blood-brain barrier by angiographic contrast material: CT and MRI studies. Neurology. 1989;39(4):567–71.
62. Sila C. Neurologic complications of cardiac tests and procedures. Handb Clin Neurol. 2014;119:41–7.
63. Wallach SG. Cannulation injury of the radial artery: diagnosis and treatment algorithm. Am J Crit Care. 2004;13(4):315–9.
64. Martin SD, Sharrock NE, Mineo R, Sobel M, Weiland AJ. Acute exacerbation of carpal tunnel syndrome after radial artery cannulation. J Hand Surg [Am]. 1993;18(3):455–8.
65. El-Ghanem M, Malik AA, Azzam A, Yacoub HA, Qureshi AI, Souayah N. Occurrence of femoral nerve injury among patients undergoing Transfemoral percutaneous catheterization procedures in the United States. J Vasc Interv Neurol. 2017;9(4):54–8.
66. Kent KC, Moscucci M, Gallagher SG, DiMattia ST, Skillman JJ. Neuropathy after cardiac catheterization: incidence, clinical patterns, and long-term outcome. J Vasc Surg. 1994;19(6):1008–13 discussion 13-4.
67. Kent KC, Moscucci M, Mansour KA, DiMattia S, Gallagher S, Kuntz R, et al. Retroperitoneal hematoma after cardiac catheterization: prevalence, risk factors, and optimal management. J Vasc Surg. 1994;20(6):905–10 discussion 10-3.
68. Dimarakis I, Protopapas AD. Vocal cord palsy as a complication of adult cardiac surgery: surgical correlations and analysis. Eur J Cardiothorac Surg. 2004;26(4):773–5.