Direct Bypass Surgery: Principles, Nuances, and Complication Avoidance

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Checklist: Direct Bypass surgery

Equipment needed	Procedural steps
Neurophysiology • Motor-evoked potentials • Somatosensory-evoked potentials • EEG to guide barbiturate-induced burst suppression Nursing • Confirm patient compliance with medication (e.g., aspirin) • Confirm pre-procedure arterial ultrasound/ Allen's test if radial artery graft planned • Review serum chemistries and blood count • Confirm availability of bypass instruments, suture material, microsuction, and papaverine Anesthesia • Procedure done under general anesthesia; routine preoperative medical clearance • Avoid hypotension, especially during induction • Induced hypertension to augment collateral circulation during temporary occlusion, as directed • Total intravenous anesthesia to facilitate neuromonitoring Neurosurgeon • Review preoperative angiography to plan for bypass and also to establish contingency plan • Operative microscope with mouthpiece and video angiography capability	Graft preparation • Harvest and preparation of donor graft (e.g., superficial temporal artery, radial artery, etc.) • Craniotomy and subarachnoid dissection to the proximal graft site Anastomosis • Temporary occlusion of recipient vessel • Arteriotomy and flushing of vessels with heparinized saline • Suturing with running Prolene • Release of temporary occlusion and reperfusion via opening of donor graft Management • Micro-Doppler confirmation of blood flow through graft and recipient vessel • Video angiography • Digital subtraction angiography postoperatively • Aspirin therapy for life

Complication Avoidance Flowchart

Complication	Cause	Remedy	Avoidance
Graft occlusion	Anastomotic stricture	Reopen the graft if immediately discovered intraoperatively; reoperation if perfusion imaging suggests territory at risk for ischemia	"Fish-mouth" opening of graft; meticulous suture technique and continuous inspection of suture line; aspirin to prevent delayed occlusion
	Thrombus	Reopen the graft if immediately discovered intraoperatively; reoperation if perfusion imaging suggests territory at risk for ischemia	Aspirin therapy
Perioperative ischemia	Hypotension resulting in decreased cerebral perfusion	Supportive care	Communication with anesthesiologist to avoid hypotension during induction and throughout the case
	Temporary occlusion during anastomosis	Supportive care	Limit time needed for suturing; burst suppression; induced hypertension

Introduction

Cerebral revascularization in the form of direct bypass (artery lumen anastomosis with another artery lumen to permit immediate blood flow) is an important tool in the treatment of a wide range of intracranial pathology. While it has a historically controversial role in the treatment of symptomatic intracranial atherosclerosis [1], few would question the utility of bypass to avert ischemia in other conditions such as complex brain aneurysms or Moyamoya disease [2–7]. The variations of bypass procedures available are diverse, with the workhorse of the superficial temporal artery-to-middle cerebral artery bypass being the most common bypass encountered in clinical practice. Other bypass procedures include extracranial-to-intracranial bypass with interposition graft, aneurysm excision with parent vessel reimplantation, intracranial-to-intracranial bypass without interposition graft, left-to-right hemisphere intracranial-to-intracranial bypass, aneurysm excision with primary reanastomosis, and intracranial-to-intracranial bypass with interposition graft, among others [8, 9]. Each operation can be tailored precisely to the patient-specific anatomy and pathology, with a bias toward simplicity and intracranial-to-intracranial solutions when possible. Even when the procedure appears to be technically sound, perioperative ischemia and graft occlusion can occur and represent the pertinent complications that must be avoided.

Preoperative Evaluation

Preoperative imaging studies are performed to thoroughly define the optimal treatment plan, contingency plans, the collateral circulation present (if any), and the size and location of the intended bypass recipient and donor vessels. This is best accomplished with digital subtraction angiography. For planning purposes of Moyamoya revascularization, the external carotid artery injection gives detailed information about the caliber and quality of the superficial temporal artery, which is the most common donor vessel. In other diseases where vessel sacrifice is planned, a balloon test occlusion can be performed, with single-photon emission computed tomography (SPECT) imaging to improve the sensitivity and specificity of a "negative" test [10, 11]. Vessel sacrifice can be considered in patients with a normal occlusion test, although the risks of a false negative must be weighed against the procedural risk of a bypass. When in doubt, a bypass procedure is favored, as it is a more predictable option than hoping for adequate collateral circulation (Fig. 18.1).

Additional testing with CT angiography can help to define the relationship of the skull base to the arterial tree, as common individual anatomical variations (aerated clinoid process, exposed petrous carotid artery segment, extradural origin of the posterior inferior cerebellar artery, etc.) are best appreciated before entering the operating room. If a flow replacement (high flow) bypass procedure is planned, then radial artery imaging with Doppler ultrasound is performed to determine both size of the radial artery and patency of the palmar arch. A failed Allen's test is a contraindication to using the radial artery as a graft [12, 13], and if both left and right sides are unsuitable, then a saphenous vein or cadaveric specimen can be considered for graft material.

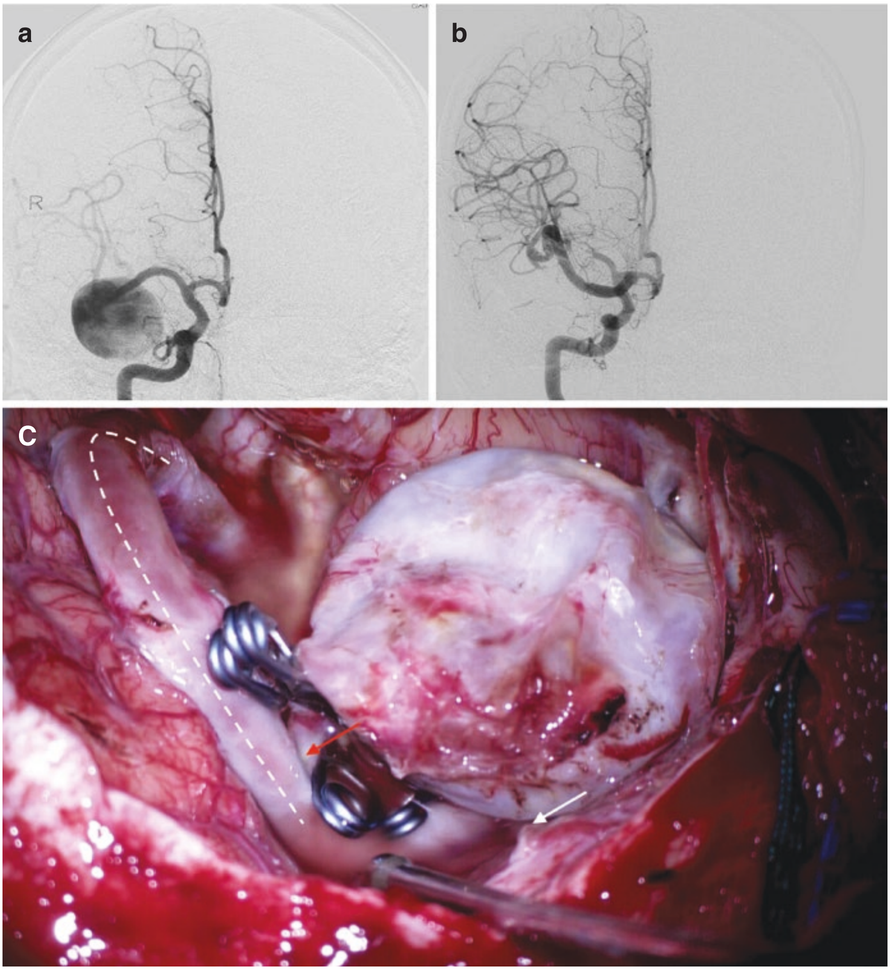

Fig. 18.1 Intracranial-to-intracranial bypass with aneurysm trapping for giant middle cerebral artery aneurysm. A 70-year-old male presented with a giant middle cerebral artery aneurysm that was producing recurrent emboli resulting in small ischemic events. (**a**) Preoperative angiography demonstrated a giant middle cerebral artery aneurysm with the middle cerebral artery trunks coming out of the base of the aneurysm. The aneurysm was not felt to be amendable to direct clipping, and a bypass was planned in order to facilitate safe aneurysm trapping. (**b**) A saphenous vein graft (*dashed line*) was used to connect a donor A1 (end to side), to the frontal M2 MCA branch (side to side, *red arrow*), as well as the temporal M2 MCA branch (end to side, *white arrow*). (**c**) Postoperative angiogram demonstrated cure of the aneurysm with preservation of blood flow in the bypass graft and the MCA branches

Since graft occlusion and perioperative ischemia are two major concerns with any revascularization procedure, patients are placed on antiplatelet aggregation agents either preoperatively or immediately postoperatively, with aspirin being the most commonly used agent. Because aspirin and clopidogrel resistance are relatively common in the general population [14, 15], various point-of-care testing assays for drug resistance may be helpful in personalization of care for these patients [16, 17].

Procedural Overview and Complication Avoidance

Flow Replacement ("High Flow Bypass," e.g., External Carotid Artery–Middle Cerebral Artery)

When a planned operation involves abrupt occlusion of a previously patent carotid artery, a flow replacement bypass is generally needed to support the blood flow requirements of the downstream territory. This type of revascularization involves an interposition graft from the external (or common) carotid artery to the proximal intracranial circulation. The patient is placed under general anesthesia and positioned supine with the head rotated to a position that is similar to what is used for a standard pterional craniotomy. This position allows for subarachnoid dissection of the Sylvian fissure and exposure of the proximal middle cerebral artery, anterior cerebral artery, and internal carotid artery. The arm is extended to the side on a supported table at a 90° angle to the body, allowing for access to the forearm in order to harvest the radial artery.

The craniotomy is performed in the usual manner, and the bone removal can be expanded to meet the specific needs of the tumor portion of the operation. Extensive subarachnoid dissection of the Sylvian fissure, with splitting of the temporal and frontal lobes apart, is helpful in opening the corridor and expanding the working angles to the proximal anastomosis site. The parietal branch of the superficial temporal artery should be preserved in continuity during the craniotomy and can be used as a salvage graft if unexpected circumstances arise during the course of the operation.

Next, the ipsilateral carotid artery bifurcation is isolated in the neck. We prefer to use a horizontal incision that follows a natural crease line of the neck skin to improve cosmetic outcome. The sternocleidomastoid muscle is mobilized laterally, along with the jugular vein. The carotid artery is isolated within the carotid sheath, and the common, internal, and external segments are marked with vessel loops. The external carotid artery is carefully inspected to ensure it is free from atherosclerosis at the planned cervical anastomosis site.

Next, or concurrently with the help of a co-surgeon, the radial artery is harvested from the forearm. Using ultrasound, the surface projection of the radial artery can be marked. An incision is made over this from the wrist all the way to the elbow joint, traversing in a linear path pointing toward the medial olecranon. The artery is bluntly dissected with scissors, and small Weck clips should be placed on the small perforating muscular branches arising from it. Closure of these branches during the dissection increases the likelihood that the graft will be free of leaks. When the full length of the artery is dissected, from the wrist to the elbow crease, temporary aneurysm clips are placed on the ends, the vessel is cut free, and the artery stumps are ligated and cauterized. The graft is marked with ink to indicate the proximal and distal ends. Heparinized saline flushes are used to clear the intraluminal blood contents. Systemic heparin is not used secondary to the high risk of hemorrhagic complications. Next, pressure distension angioplasty is performed by distal occlusion of the graft and injecting it with heparinized saline using manual syringe pressure. This minimizes the risk of graft vasospasm and also identifies occult leaks that can be closed with 10-0 nylon suture. The ends of the graft are cleared of adherent connective tissue under microscopic vision to prepare for the anastomosis. The distal end of the graft is "fish mouthed" by cutting it at a 60° angle, followed by using scissors to open a few contiguous millimeters along the more proximal portion of the graft. The footprint this creates is a diamond shape, which ensures that the anastomosis site diameter doesn't become smaller than the average graft diameter, even in the setting of sewing.

After identifying the proximal segment of the middle cerebral artery or internal carotid artery where the anastomosis will be performed, temporary clips are then placed on the cerebral vessel to isolate the segment from the circulation. During this period, the amount of time the blood vessel can be occluded without resulting in stroke is highly variable. It appears to be dependent on many patient-specific factors, such as collateral circulation from other vascular territories, although the variability in maximally tolerated ischemia time from patient to patient is not well understood. Patients are closely monitored with somatosensory-evoked potentials and motor-evoked potentials in order to detect the onset of early ischemic changes. Measures to augment blood flow through collateral circulation, including temporary induced systemic hypertension, are thought to be helpful and are routinely used [18]. Alternative strategies to maximize the ischemia window are centered on decreasing cerebral metabolic demand. Studies have examined the use of mild hypothermia [19], although this was not found to be beneficial in patients undergoing surgery for ruptured brain aneurysms. Its potential benefit in patients undergoing elective procedures, or more specifically those undergoing temporary occlusion of cerebral arteries, is not well studied. Another technique frequently used to decrease cerebral metabolic demand is anesthetic-induced electroencephalographic (EEG) burst suppression. Burst suppression is an EEG pattern in which high-voltage activity alternates with isoelectric quiescence. It is characteristic of an "inactivated" brain, is seen with deep levels of general anesthesia, and is thought to be associated with a decrease in cerebral metabolic rate coupled with the stabilizing properties of ATP-gated potassium channels [20]. In clinical practice, the rate of infusion of an anesthetic (typically propofol) can be manipulated by the anesthesiologist based on real-time feedback from continuous EEG monitoring in order to achieve 100% intensity burst suppression. The neuroprotective benefit of this technique to extend the ischemic window is a subject of ongoing investigation. The radial artery is then grafted to the intracranial anastomosis site using continuous nylon suture, usually 9-0 or 10-0. The heel and toe sites are anchored first, and then the needle is passed from extraluminal to intraluminal down each suture line. After all of the passes have been made, forceps are then used to carefully tighten the suture. Alternatively, an interrupted suturing technique can be used. The temporary aneurysm clips are then released, completing the distal portion of the bypass.

The radial artery graft is then tunneled from the craniotomy opening down to the cervical opening through a chest tube passed with a Kelly clamp in order to protect the graft. The external carotid artery anastomosis site is identified, marked, and then isolated with aneurysm clips. An arteriotomy is made in the external carotid artery, allowing for introduction of an aortic punch to create a larger opening. The proximal portion of the radial artery graft is then sewn to this site using 8-0 nylon suture with a continuous technique. After the temporary aneurysm clips are released, there is usually some amount of bleeding from the anastomosis site. This is controlled with surgical fibrillar (Ethicon) or similar absorbable hemostatic agent. Foam-based hemostatic agents with thrombin additives are avoided. Next careful inspection of the vessels is performed to confirm patency. Micro-Doppler can be used, along with video angiography (indocyanine green or sodium fluorescein). Once satisfied, a permanent aneurysm clip can be placed to proximally occlude the intracranial carotid artery. Alternatively, endovascular proximal occlusion can be performed with intermittent digital subtraction angiography as a gold standard to confirm graft patency. Continuous blood pressure monitoring in the intensive care unit for the first day after the procedure is standard in order to ensure normotension and euvolemia. Postoperative aspirin is administered as soon as the patient is awake and able to tolerate oral intake and is continued indefinitely. It is felt that aspirin decreases the short-term rate of thromboembolism and improves long-term rates of graft patency, drawing on the experience of aortocoronary bypass [21–23].

Flow Augmentation (Superficial Temporal Artery–Middle Cerebral Artery)

In certain cases, such as Moyamoya disease, flow augmentation can restore adequate blood flow and alleviate hemodynamic insufficiency. For this procedure, there is no interposition graft, and the donor vessel is a transposed superficial temporal artery (STA) with its origin left in situ. The patient is placed under general anesthesia and positioned with their head horizontal to the floor. The course of the STA is mapped with ultrasound, and an incision over the surface projection of it, from just above the zygoma to the just above the superior temporal line, is made under microscope magnification. The subcutaneous tissues are dissected bluntly with scissors, and the STA is exposed. The frontal branch of the artery can also be dissected for several centimeters and preserved as a contingency graft. The parietal branch is covered in a rubber sling and moved to the side in preparation for the craniotomy. The exposed temporalis muscle is then incised into four quadrants, and fishhook-style retractors are placed. The temporal craniotomy is then performed directly over the Sylvian fissure, taking care to protect the STA. The dura is opened in a stellate fashion, and the subarachnoid dissection of the exposed middle cerebral artery M3 and M4 segments is performed. A good recipient site is typically one with large caliber, free of atherosclerosis, and has a course that leads most directly to the proximal middle cerebral artery within the Sylvian fissure. There is a balance between selecting a more proximal vessel, which carries the risk of ischemia from temporary occlusion over a greater territory, and selecting a vessel large enough to support blood flow from the STA (Fig. 18.2).

Next, a temporary aneurysm clip is placed on the distal end of the dissected STA, and it is ligated distally, thereby freeing it from its attachment. The vessel is flushed with heparinized saline. The most distal end of the artery to be used in the anastomosis is cleaned of connective tissue and fish mouthed as previously described.

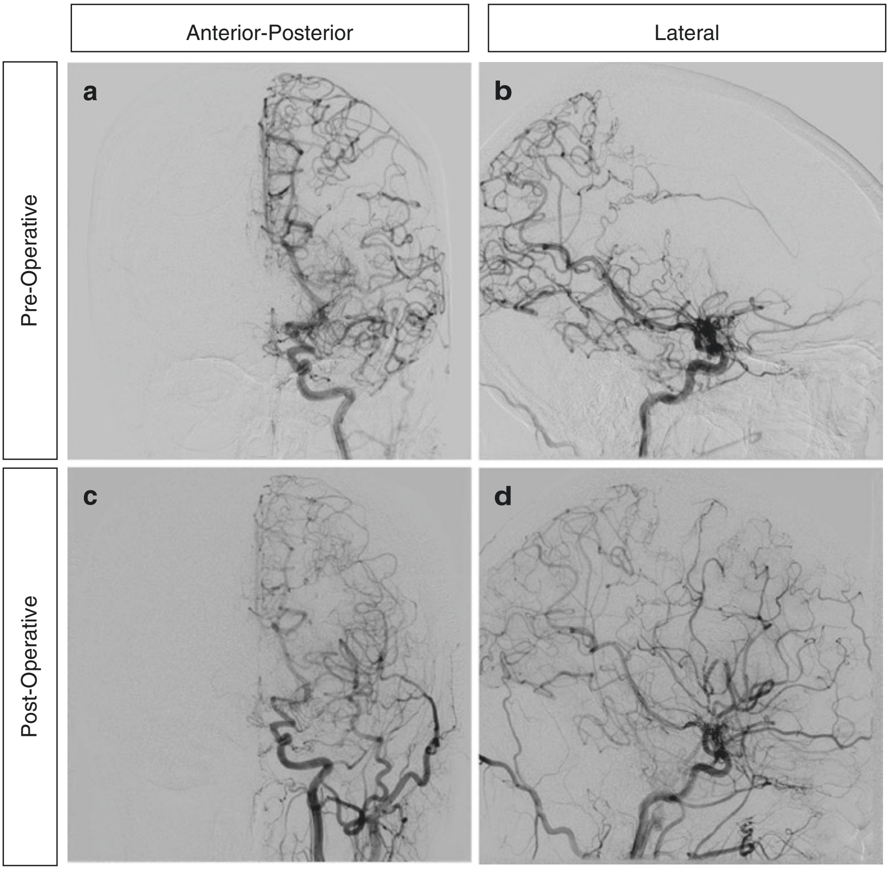

Fig. 18.2 Superficial temporal artery-to-middle cerebral artery bypass for Moyamoya disease. A woman in her 30s presented with Moyamoya disease and a hemorrhagic event. (**a** and **b**) After a period of recovery, preoperative digital subtraction angiography demonstrated near occlusion of her distal carotid artery and a paucity of blood flow through much of the anterior circulation on the patient's left side following carotid artery injection. (**c** and **d**) A superficial temporal artery-to-middle cerebral artery bypass was performed resulting in profound revascularization of the middle cerebral artery territory

Next, the recipient site is isolated with temporary aneurysm clips, and a beveled needle is used to perform an arteriotomy. Microscissors are used to extend the arteriotomy in a line along the MCA that matches the length of the diameter of the prepared STA. The STA is then approximated to the recipient site with heel and toe stitches using 10-0 nylon suture. The suture lines are then completed using these continuous running sutures. Other aspects of the operation, including neuromonitoring, graft inspection, and perioperative management, are similar to those described for flow replacement bypass.

Complication Management

A major complication of direct bypass surgery is graft occlusion with thrombus. This can be detected either at the time of surgery, in the immediate postoperative period, or at some delayed interval. Careful inspection of the graft immediately after the anastomosis and before closing the craniotomy provides an opportunity to detect this complication prior to ischemia. If video angiography and micro-Doppler detect occlusion or inadequate flow, the graft should be reexplored immediately by reoccluding the recipient vessel and opening the suture line. Thrombus can be extracted and the vessel/graft lumen irrigated with heparinized saline. The bypass is then repeated, always taking care to avoid stricture at the anastomosis site. In the immediate postoperative period, if graft occlusion is detected as a result of surveillance angiography, perfusion imaging can be obtained to ascertain whether any mismatch is present between blood flow, blood volume, and transit time in the graft territory. If asymptomatic, or without significant mismatch, the complication can be managed expectantly. If an ischemic penumbra is present, then the graft should be reexplored immediately as described above. Occlusion in the delayed interval (months to years) rarely occurs, and repeated revascularization can be considered in unique scenarios when symptomatic or when significant at-risk territory exists.

Conclusions

Complication avoidance in direct bypass surgery focuses on the prevention of perioperative ischemia and graft occlusion. Patient selection, meticulous microsurgical technique, antiplatelet aggregation agents, and intraoperative neuroprotection strategies are the main tenants needed for successful outcomes.

References

1. Powers WJ, Clarke WR, Grubb RL, et al. Extracranial-intracranial bypass surgery for stroke prevention in hemodynamic cerebral ischemia: the carotid occlusion surgery study randomized trial. JAMA. 2011;306(18):1983–92.
2. Sanai N, Zador Z, Lawton MT. Bypass surgery for complex brain aneurysms: an assessment of intracranial-intracranial bypass. Neurosurgery. 2009;65(4):670–83.
3. Mesiwala AH, Sviri G, Fatemi N, Britz GW, Newell DW. Long-term outcome of superficial temporal artery–middle cerebral artery bypass for patients with moyamoya disease in the US. Neurosurg Focus. 2008;24(2):E15.
4. Guzman R, Lee M, Achrol A, et al. Clinical outcome after 450 revascularization procedures for moyamoya disease: clinical article. J Neurosurg. 2009;111(5):927–35.
5. Kalani MYS, Zabramski JM, Nakaji P, Spetzler RF. Bypass and flow reduction for complex basilar and vertebrobasilar junction aneurysms. Neurosurgery. 2013;72(5):763–76.
6. Abla AA, McDougall CM, Breshears JD, Lawton MT. Intracranial-to-intracranial bypass for posterior inferior cerebellar artery aneurysms: options, technical challenges, and results in 35 patients. J Neurosurg. 2016;124(5):1275–86.

7. Rutledge WC, Choudhri O, Walcott BP, et al. Indirect and direct revascularization of ACTA2 cerebral arteriopathy: feasibility of the superficial temporal artery to anterior cerebral artery bypass with posterior auricular artery interposition graft: case report. J Neurosurg Pediatr. 2016;18(3):339–43.
8. Pisapia JM, Walcott BP, Nahed BV, Kahle KT, Ogilvy CS. Cerebral revascularization for the treatment of complex intracranial aneurysms of the posterior circulation: microsurgical anatomy, techniques and outcomes. J Neurointerv Surg. 2011;3(3):249–54.
9. Lawton MT, Walcott BP, Stapleton CJ. Middle cerebral artery-to-A1 anterior cerebral artery intracranial-intracranial bypass for ruptured dissecting pseudoaneurysm: 3-dimensional operative video. Oper Neurosurg. 2016;12(1):91–2.
10. Abud DG, Spelle L, Piotin M, Mounayer C, Vanzin JR, Moret J. Venous phase timing during balloon test occlusion as a criterion for permanent internal carotid artery sacrifice. Am J Neuroradiol. 2005;26(10):2602–9.
11. Sugawara Y, Kikuchi T, Ueda T, et al. Usefulness of brain SPECT to evaluate brain tolerance and hemodynamic changes during temporary balloon occlusion test and after permanent carotid occlusion. J Nucl Med. 2002;43(12):1616–23.
12. Jarvis MA, Jarvis CL, Jones PR, Spyt TJ. Reliability of Allen's test in selection of patients for radial artery harvest. Ann Thorac Surg. 2000;70(4):1362–5.
13. Starnes SL, Wolk SW, Lampman RM, et al. Noninvasive evaluation of hand circulation before radial artery harvest for coronary artery bypass grafting. J Thorac Cardiovasc Surg. 1999;117(2):261–6.
14. Krasopoulos G, Brister SJ, Beattie WS, Buchanan MR. Aspirin "resistance" and risk of cardiovascular morbidity: systematic review and meta-analysis. BMJ. 2008;336(7637):195–8.
15. Matetzky S, Shenkman B, Guetta V, et al. Clopidogrel resistance is associated with increased risk of recurrent atherothrombotic events in patients with acute myocardial infarction. Circulation. 2004;109(25):3171–5.
16. Price MJ, Endemann S, Gollapudi RR, et al. Prognostic significance of post-clopidogrel platelet reactivity assessed by a point-of-care assay on thrombotic events after drug-eluting stent implantation. Eur Heart J. 2008;29(8):992–1000.
17. Roberts JD, Wells GA, Le May MR, et al. Point-of-care genetic testing for personalisation of antiplatelet treatment (RAPID GENE): a prospective, randomised, proof-of-concept trial. Lancet. 2012;379(9827):1705–11.
18. Shuaib A, Butcher K, Mohammad AA, Saqqur M, Liebeskind DS. Collateral blood vessels in acute ischaemic stroke: a potential therapeutic target. Lancet Neurol. 2011;10(10):909–21.
19. Todd MM, Hindman BJ, Clarke WR, Torner JC. Mild intraoperative hypothermia during surgery for intracranial aneurysm. N Engl J Med. 2005;352(2):135–45.
20. Ching S, Purdon PL, Vijayan S, Kopell NJ, Brown EN. A neurophysiological–metabolic model for burst suppression. Proc Natl Acad Sci U S A. 2012;109(8):3095–100.
21. Gavaghan TP, Gebski V, Baron D. Immediate postoperative aspirin improves vein graft patency early and late after coronary artery bypass graft surgery. A placebo-controlled, randomized study. Circulation. 1991;83(5):1526–33.
22. Chesebro JH, Fuster V, Elveback LR, et al. Effect of dipyridamole and aspirin on late vein-graft patency after coronary bypass operations. N Engl J Med. 1984;310(4):209–14.
23. Van der Meer J, Hillege H, van Gilst W, et al. Prevention of one-year vein-graft occlusion after aortocoronary-bypass surgery: a comparison of low-dose aspirin, low-dose aspirin plus dipyridamole, and oral anticoagulants. Lancet. 1993;342(8866):257–64.