A recent study demonstrated that the number of cerebral bypasses increased from 2002 to 2014. This study also demonstrated that the number of bypasses for moyamoya disease (MMD) increased, whereas atherosclerotic occlusive disease and flow replacement bypasses for aneurysms decreased during the same period. Cerebral bypass remains an important tool in the current endovascular era, and it is important for cerebrovascular surgeons to keep up with the evolving indications, as technology and our understanding of cerebral hemodynamics evolve.

Cerebral bypass surgery currently includes 2 large categories: flow augmentation and flow replacement. Flow augmentation involves ischemic pathophysiology such as MMD, moyamoya syndrome (MMS), and atherosclerotic steno-occlusive disease (SOD). Flow replacement refers to bypass used in open cerebrovascular and skull base tumor surgery when a vessel cannot be preserved with standard surgical techniques (eg, trapping and bypass of aneurysm, vascular encasement, or unintended/planned vessel injury during tumor removal).

Flow Augmentation Bypass
In the hemodynamic phase of cerebral bypass surgery for ischemia, patients are carefully evaluated for hemodynamic compromise despite best medical management when considering them for flow augmentation procedures.

Moyamoya Disease and Moyamoya Syndrome
MMD is a progressive arteriopathy that leads to idiopathic intimal thickening and narrowing of the intracranial internal carotid arteries and can involve the proximal anterior and middle cerebral arteries (MCAs). There is compensatory enlargement of small vessels near the apex of the internal carotid that provide collateral flow. The angiographic appearance of these small vessels was first described in 1957 by the Japanese term "moyamoya" or puff of smoke. MMS is a term used to describe patients who have the same characteristics as MMD but have well-known recognized associated conditions such as sickle cell disease, Down syndrome, prior radiotherapy, among others. There are no medical treatments that can halt the progression or reverse the vasculopathy. Surgical revascularization is considered the only effective therapy.

Clinical Examination
The first and most important part of deciding whether a bypass is indicated is the clinical status of the patient. A patient who has had repeated attacks despite being on...
appropriate medical therapy is a much different scenario than an asymptomatic patient with imaging findings. Patients with MMD often present with infarcts, transient ischemic attacks, intraparenchymal hemorrhages, or a combination of all the above.

The important clinical information to understand is the number of events that have happened, their time course, and evidence that the symptoms are related to decreased perfusion or dehydration of the patient. This is especially important in patients with MMS due to sickle cell disease.

Imaging

The imaging obtained includes an MRI to assess for evidence of ischemia on diffusion-weighted imaging (DWI) or other findings of ischemia such as an “ivy sign” on fluid-attenuated inversion recovery (FLAIR) imaging indicating a low-flow state. In addition to MRI, an advanced perfusion study such as a CT perfusion, MRI perfusion, or MRI arterial spin labeling study is obtained to further clarify the zone of ischemia that is present.

Physiologic Testing

Additional workup includes transcranial Doppler (TCD) to measure vasomotor reactivity (VMR) and to identify patients with misery perfusion who have little ability to compensate for a low-flow ischemic state.

Angiography

Angiography is performed to confirm the diagnosis and to assess the severity of disease and collateralization pattern. There are often circle of Willis (COW) collaterals present through the anterior communicating artery (ACOMM) or posterior communicating artery (PCOMM). There are also leptomeningeal collaterals that typically arise from the posterior cerebral artery (PCA) and collateralize with the splenial branch of the anterior cerebral artery (ACA) (Figure 1).

Lastly, there are extradural collaterals that develop from the meningeal and scalp arteries such as the middle meningeal artery and the superficial temporal artery (Figure 2).

The severity of the disease and the number of collaterals present aid in understanding the severity of the patient’s disease and their ability (or inability) to overcome the flow deficit through collaterals. Evaluation of the capillary phase in each of these separate collateralization patterns can aid in a deeper understanding of the area most at risk. This can also help guide the location of an intended bypass (ie, ACA, MCA, and PCA distribution).

Figure 1. Leptomeningeal collateralization (white arrow) and retrograde COW collateralization from the PCOMM (black arrow).
Supporting Literature

The literature reliably shows that there is a significant annual stroke rate in untreated patients with MMD and MMS (13%) with high rates of disease progression. Several large studies, primarily from the Japanese literature and more recently in the North American literature, have shown favorable results for flow augmentation in MMD and MMS in both adults and children. Consequently, randomized controlled trials (RCTs) are unlikely to be carried out to test the efficacy of revascularization surgery for the prevention of stroke. Additionally, the Japanese adult moyamoya trial demonstrated a decrease in rebleeding in hemorrhagic moyamoya after direct bypass surgery. Surgery is recommended for both children and adults who are symptomatic with hemodynamic compromise (Figure 3).

Pearls

- Carefully understand the clinical presentation of the patient and the time course of events.
- Review angiography to evaluate for collateralization patterns, especially the capillary phases of the different collaterals.
- Obtain confirmatory physiologic testing or advanced imaging to confirm a low-flow uncompensated state.

Atherosclerotic Steno-occlusive Disease

Clinical Examination

Clinical examination of a patient with SOD should include a thorough evaluation of risk factors for atherosclerosis (smoking, obesity, cardiovascular disease, and family history). The time course of the patient’s ischemic events should be carefully understood, as it relates to the interventions (medical, surgical, or endovascular) that have been performed before presentation. A patient who has failed dual antiplatelets, endovascular stenting, or carotid endarterectomy but still presents with debilitating ischemic events is much different than a patient with a single ischemic attack without undergoing best medical therapy.

A patient who has had repeated ischemic attacks with a carotid occlusion despite being on appropriate medical therapy presents a stark difference from an asymptomatic patient with a carotid occlusion. Patients with symptomatic carotid occlusion are at high risk for subsequent ipsilateral stroke, ranging from 2% to 6% per year, with the risk being much lower in patients who are asymptomatic.

Imaging

The imaging obtained in SOD typically includes an MRI to evaluate the ischemic burden present. This is important as a patient with a small ischemic burden and hypoperfusion has more brain tissue to save than a completed large-volume ischemic stroke. Vascular cross-sectional imaging such as a CT angiography (CTA) or MR angiography (MRA) is often performed to aid in diagnosis. The site of stenosis or occlusion is carefully evaluated. Patients with carotid stenosis are considered first for carotid endarterectomy or endovascular stenting. Patients with intracranial atherosclerosis are considered for antiplatelet therapy or intracranial stenting. Advanced imaging such as a CT perfusion, MR perfusion, or an MRI arterial spin labeling study is often performed to further quantify the area of low-flow ischemia.

Physiologic Testing

All patients with SOD being considered for bypass surgery undergo thorough physiologic testing using TCD and VMR evaluations. This helps define better the patient’s ability (or inability) to compensate for their ischemic state.

Angiography

All patients undergo angiography to assess for collateralization. The collateralization pattern in SOD is often different than in MMD and MMS. The collaterals here are
These patients often harbor other cardiovascular disease, and a thorough preoperative workup is a necessity to ensure that perioperative morbidity is minimized.

**Flow Replacement Bypass**

**Considerations**

When reviewing indications for flow replacement, the neurosurgeon must consider whether a vessel needs to be sacrificed and replaced. The logical next question follows: Does the patient have enough collateral vessels, or is a bypass necessary?

**Clinical Examination**

The clinical examination of a patient being considered for flow replacement should first begin with a thorough understanding of the indication for performing the primary procedure and the potential consequences. A patient with terminal head and neck cancer may not need to undergo an aggressive resection with a bypass if they only have months left to live. An unruptured aneurysm necessitating a bypass poses a higher level of surgical complexity, and the indication for treating it should be thoroughly investigated. These situations challenge surgeons to weigh the risks and benefits of deconstructing or reconstructing the cerebral vasculature in the face of achieving radical resections of skull base lesions or in the treatment of complex aneurysms unable to otherwise be treated (Figure 4).

There are some advocates for a "universal revascularization" approach for patients undergoing large vessel occlusions. However, this strategy leads to some patients undergoing unnecessary revascularization. Additionally, there is a known 1% to 2% rate of delayed ischemic complications after carotid ligation and a 1% to 10% risk of de novo aneurysm formation. For these reasons, it has been our strategy to consider a selective revascularization strategy for patients.

**Imaging**

Cross-sectional imaging including CTA or MRA is typically obtained. We often obtain a CTA at our institution to understand the location of the proposed bypass and the potential donor sites and the intended site of a potential bypass and vessel sacrifice.

**Physiologic Testing**

The patient should undergo a balloon test occlusion to evaluate whether there are enough collaterals to tolerate parent vessel sacrifice without a bypass. If the patient has any significant evidence of venous delay on this imaging study, a bypass should be considered.

**Angiography**

Angiography is often performed to assess the potential donor and recipient sites and the intended site of parent vessel occlusion. The collateral pattern is also assessed to better understand the patient’s cerebrovascular reserve.

**Supporting Literature**

Because of the rarity and variety of these lesions, there are no large RCTs available to test the value of bypass for...
treatment of patients with complex aneurysms or in sacrificing and bypassing a vessel in patients with skull base tumors. Additionally, the continued development of endovascular technology has decreased the indications for flow preservation bypass in intracranial aneurysm surgery. Several case series continue to show that there is clearly a role for bypass in both aneurysm and skull base surgery, even in the modern endovascular era.

**Pearls**

- Cerebral revascularization for skull base lesions is often a last resort option, when no better option for treatment exists, and there is a reasonable chance of oncologic or neurologic benefit.
- We prefer a selective rather than a universal flow replacement strategy due to the risk of ischemia and de novo aneurysm formation associated with flow replacement.
- The caliber of the vessel being targeted should be considered when choosing an appropriate donor vessel.

**Readings**


- The caliber of the vessel being targeted should be considered when choosing an appropriate donor vessel.

**Readings**


1. An Ivy sign is an angiographic finding in MMD.  
   True or False?

2. The Japanese adult moyamoya trial demonstrated an increase in rebleeding after direct bypass surgery.  
   True or False?

3. Untreated patients with MMD and MMS have an annual stroke rate of 4%.  
   True or False?

4. There is a 1% to 10% risk of de novo aneurysm formation after carotid ligation.  
   True or False?

5. The rate of ipsilateral stroke in patients with symptomatic carotid artery occlusion is 2% to 6%.  
   True or False?

6. The COSS trial was stopped early due to an ipsilateral stroke rate of 21% in the surgical arm and 23% in the medical arm.  
   True or False?

7. The perioperative stroke rate in the surgical group in the COSS trial was 4%.  
   True or False?

8. The main criticism of the EC-IC study (1985) was the lack of hemodynamic criteria for patient selection.  
   True or False?

9. The collateralization pattern is often different in MMD and MMS compared with atherosclerotic SOD.  
   True or False?

10. A balloon test occlusion is used in a “universal” bypass strategy.  
    True or False?