The future of open vascular neurosurgery: perspectives on cavernous malformations, AVMs, and bypasses for complex aneurysms

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Despite the erosion of microsurgical case volume because of advances in endovascular and radiosurgical therapies, indications remain for open resection of pathology and highly technical vascular repairs. Treatment risk, efficacy, and durability make open microsurgery a preferred option for cerebral cavernous malformations, arteriovenous malformations (AVMs), and many aneurysms. In this paper, a 21-year experience with 7348 cases was reviewed to identify trends in microsurgical management. Brainstem cavernous malformations (227 cases), once considered inoperable and managed conservatively, are now resected in increasing numbers through elegant skull base approaches and newly defined safe entry zones, demonstrating that microsurgical techniques can be applied in ways that generate entirely new areas of practice. Despite excellent results with microsurgery for low-grade AVMs, brain AVM management (836 cases) is being challenged by endovascular embolization and radiosurgery, as well as by randomized trials that show superior results with medical management. Reviews of ARUBA-eligible AVM patients treated at high-volume centers have demonstrated that open microsurgery with AVM resection is still better than many new techniques and less invasive approaches that are occlusive or obliterative. Although the volume of open aneurysm surgery is declining (4479 cases), complex aneurysms still require open microsurgery, often with bypass techniques. Intracranial arterial reconstructions with reimplantations, reanastomoses, in situ bypasses, and intracranial interpositional bypasses (third-generation bypasses) augment conventional extracranial-intracranial techniques (first- and second-generation bypasses) and generate innovative bypasses in deep locations, such as for anterior inferior cerebellar artery aneurysms. When conventional combinations of anastomoses and suturing techniques are reshuffled, a fourth generation of bypasses results, with eight new types of bypasses. Type 4A bypasses use in situ suturing techniques within the conventional anastomosis, whereas type 4B bypasses maintain the basic construct of reimplantations or reanastomoses but use an unconventional anastomosis. Bypass surgery (605 cases) demonstrates that open microsurgery will continue to evolve. The best neurosurgeons will be needed to tackle the complex lesions that cannot be managed with other modalities. Becoming an open vascular neurosurgeon will be intensely competitive. The microvascular practice of the future will require subspecialization, collaborative team effort, an academic medical center, regional prominence, and a large catchment population, as well as a health system that funnels patients from hospital networks outside the region. Dexterity and meticulous application of microsurgical technique will remain the fundamental skills of the open vascular neurosurgeon.

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KEYWORDS aneurysm; arteriovenous malformation; bypass; cavernous malformation; cerebral revascularization; endovascular surgery; microsurgery; vascular disorders

M^Y (M.T.L.) neurosurgical career spans more than one-third of the history of the *Journal of Neurosurgery* (JNS) and has included some of the most tumultuous events for the cerebrovascular specialty: the first Gamma Knife in the US in 1987, Guglielmi detach-

able coils in 1991, the International Subarachnoid Aneurysm Trial in 1999, the International Study on Unruptured Intracranial Aneurysms in 2003, Onyx liquid embolic material in 2005, and the Pipeline endovascular device in 2011.^{5,16,36,37,41,69} A flurry of studies continued the innova-

ABBREVIATIONS A1 ACA = first segment of anterior cerebral artery; a2 AICA = second segment of AICA; a3 AICA = third segment of AICA; AICA = anterior inferior cerebellar artery; ARUBA = A Randomized Trial of Unruptured Brain Arteriovenous Malformations; AVM = arteriovenous malformation; CCM = cerebral cavernous malformation; EC-IC = extracranial-intracranial; ECA = external carotid artery; ICA = internal carotid artery; M2 MCA = second segment of MCA; MCA = middle cerebral artery; p3 PICA = third segment of PICA; PICA = posterior inferior cerebellar artery; RAG = radial artery graft; STA-MCA = superficial temporal artery–middle cerebral artery.

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tive trend including the Carotid Occlusion Surgery Study in 2011, A Randomized Trial of Unruptured Brain Arteriovenous Malformations (ARUBA) in 2014, and multiple clinical trials validating the efficacy of mechanical thrombectomy for acute ischemic stroke caused by large vessel occlusion in 2015.^{14,40,49} These events eroded the microsurgical case volume and threatened the future of open vascular neurosurgery, shifting market forces and patient attitudes toward alternative endovascular and radiosurgical therapies. These three decades transformed vascular neurosurgery into a multimodal specialty with different skill sets, distinct training programs, and the possibility of asymmetrical or disharmonious interests of individual practitioners.

I was attracted to open vascular neurosurgery by its demand for dexterity: steady hands, precision movements, and meticulous technique. Dexterity is the magic that makes surgical feats happen in deep corridors of the brain. As a Barrow Neurological Institute resident, I observed a master neurosurgeon clipping basilar aneurysms under hypothermic circulatory arrest and suturing complex bypasses in some of the most beautiful and heroic operations I had seen.^{28,32} With patients coming to Phoenix from around the world, it occurred to me that such complex vascular lesions demanded highly technical repairs rather than high technology, and extreme dexterity was in short supply. The technical challenge, spectacular anatomy, and acute need made my career decision easy then, but what about today? Would I make the same choice I made 25 years ago? My answer is based on lessons from experiences with cerebral cavernous malformations (CCMs), arteriovenous malformations (AVMs), and bypasses for aneurysms (Fig. 1): Microsurgical technique can be applied in ways that generate entirely new areas of practice, open microneurosurgery remains superior to many new technologies and less invasive approaches, and innovation and evolution continue to advance open microsurgery despite its long tradition and maturity.

Expanding Open Microsurgery: Brainstem Cavernous Malformations

From Inoperable to Operable

Not long ago, neurosurgeons believed the brainstem was a surgical no-man's-land where densely packed cranial nerve nuclei and ascending and descending neural tracts prevented operative transgression. Walter Dandy is credited with the first accurate diagnosis and successful removal of a brainstem CCM in 1934, but few cases were documented in the following decades because neurosurgeons considered intervention too dangerous.⁶⁶ With the advent of MRI in the 1980s, CCMs were characterized as pathological entities with pathognomonic findings including a "popcorn" appearance, hemosiderin rings, and mixed signal intensities.⁵² CCMs were more amenable to resection than AVMs because they lacked arterial input and could be removed piecemeal. With these insights, a handful of brave vascular neurosurgeons advanced the idea that the brainstem was not inviolable territory and that brainstem CCMs were not inoperable lesions.^{59,68}

Robert Spetzler and colleagues published their first ex-

perience with 24 symptomatic brainstem CCMs in 1991, selecting 16 patients for surgery based on neurological status, number of hemorrhages, and the lesion's proximity to the pial surface.⁷⁴ All but one patient's neurological outcome improved postoperatively, leading to the recommendation of surgery for symptomatic patients. My arrival in Phoenix as a resident coincided with this publication, and I experienced the wave of referrals to Barrow Neurological Institute from around the world. That referral network, combined with the local Hispanic patient population in whom CCMs were so prevalent, reinforced the breakthrough that microsurgery for brainstem CCMs was often safe and advisable.⁴⁷ This convergence of available cases and a master who practiced both high-level microsurgery and skull base surgery shaped a new discipline within vascular neurosurgery.

Brainstem Microsurgery

Brainstem CCM surgery began with simple concepts like the "two-point method" to select the best surgical approach.⁸ Complex skull base exposures that had been developed for tumors and aneurysms were adapted to the pathology of CCMs (Fig. 2). For example, the orbitozygomatic approach, developed for high-riding basilar bifurcation aneurysms, was ideal for midbrain CCMs in the cerebral peduncle, interpeduncular fossa, and contralateral cerebral peduncle. Brainstem microsurgery utilized navigation for submerged lesions, tractography for lesions near motor pathways, and lighted microinstruments for deep corridors. The perception of the brainstem as an impenetrable monolith transformed as CCMs below the pial surface were reached through safe entry zones (Fig. 3).¹ Thanks to the pioneering efforts of courageous vascular neurosurgeons, brainstem CCMs both on and beneath the pia are resected as first-line management at centers around the world.

Spetzler and colleagues have described over 400 brainstem CCM resections, which showcase the birth of an elegant discipline within open microsurgery.⁷³ My microsurgical experience with 227 brainstem CCMs and 834 CCMs overall demonstrates a growth trend (Fig. 1) for CCMs.¹³ The story of the brainstem CCM, from early misdiagnosis to initial conservative management to current state of the art, is a testament to the open microsurgical technique, its application to a newly defined lesion, and its curative efficacy. With no endovascular or proven radiosurgical alternative, microsurgery occupies the dominant position in the therapeutic algorithm. Brainstem CCMs demonstrate that microsurgical skills are versatile, our surgical approaches can be refined (Supplementary Table 1), our repertoire can be expanded, and our techniques can become increasingly honed.⁶⁷ Treatment of brainstem CCMs is a story of success and optimism that seemingly came out of nowhere.

Defending Open Microsurgery: AVMs

The Learning Curve

AVMs are freaks of nature, explosions of hemodynamic energy and red fury, with dilated arteries converging from all directions like angry snakes, engorged veins twisting and throbbing from turbulent shunts, and a glistening

FIG. 1. Annual number of open microsurgical procedures performed by one of the authors (M.T.L.) for CCMs (A), brain AVMs (B), aneurysms (C), and bypasses (D), 1997–2018. Cumulative number of open microsurgical procedures performed for brain aneurysms (E) and cumulative number of open microsurgical procedures for CCMs, brain AVMs, and bypasses (F).

arachnoid veil concealing the tangled beast within. Learning to tame these beasts is arduous. Two decades, 836 AVMs, and one textbook later, AVM surgery has become a staple in my practice. I have learned that each AVM is not unique, but one of 32 recognizable AVM subtypes that can be anatomically deciphered and surgically attacked (Fig. 4 and Supplementary Table 2).²³ I have learned that surgical patients must be chosen wisely, relying on both grading systems that are modified, supplemented, and evolving and a strong surgeon-patient relationship that considers the patient's condition, concerns, and expectations.^{25,29} I have learned to study thoroughly the radiographic and angiographic anatomy for landmarks that will guide me in the

surgical battle. I have learned to rely on battle plans for AVM resection and to execute them methodically while maintaining absolute hemostasis and control.

This militaristic description is intentional because unlike aneurysm surgery, which can be choreographed, practiced, and performed like a dance, AVM surgery is like war. Like a general sizing up the enemy, management options are evaluated, and anatomy is surveyed radiographically. Like a battlefield, brain tissue containing an AVM is mapped for eloquent cortex and tracts that are landmines during dissection. Arterial feeders are destroyed early, like enemy supply lines; draining veins are preserved, like runways and bridges; and circumferential AVM dissection

FIG. 2. Surgical approaches to brainstem CCMs depicted in anterior (A), lateral (B and C), and posterolateral (D) views. Surgical approaches to aneurysms and skull base tumors, such as the far lateral approach to posterior inferior cerebellar artery (PICA) aneurysms and the supracerebellar-infratentorial approach to tentorial meningiomas, were adapted and applied to brainstem CCMs. Midbrain CCMs are resected anteriorly through an orbitozygomatic-transsylvian approach (A); laterally through a subtemporal approach (B); or posterolaterally through a lateral supracerebellar-infratentorial approach, posteriorly through a midline supracerebellar-infratentorial approach, and superiorly through a bifrontal-transcallosal-transchoroidal approach (D). Pontine CCMs are resected laterally through a retrosigmoid-cerebellopontine angle approach or a retrosigmoid-transmiddle cerebellar peduncle approach (C), laterally through a petrosal approach, inferolaterally through a far lateral-transpontomedullary sulcus approach (C), and posteriorly through a suboccipital transventricular or suboccipital telovelar approach (D). Medullary CCMs are resected posteriorly through a suboccipital approach (D) or laterally through a far lateral approach (C). Used with permission from Barrow Neurological Institute, Phoenix, Arizona.

in brain parenchyma flanks the enemy on multiple fronts. Preoperative embolization or radiosurgery is ordered, like a bombing raid, but defeating an AVM usually requires hand-to-hand combat by the neurosurgical soldier. AVM

surgery is more than just the execution of technical steps with predictable outcomes. With skill, attention, precision, cunning, and endurance, the neurosurgeon achieves excellent outcomes. In our *JNS* review of 232 consecutive

FIG. 3. Safe entry zones were discovered to access CCMs not present on the brainstem's pial surface, enabling precious millimeters of normal-appearing tissue to be transgressed to reach target CCMs without morbidity. Nine safe entry zones (purple regions; dashed lines indicate the access trajectory) are shown, including 3 in the midbrain, 2 in the pons, and 4 in the medulla: 1) anterior mesencephalic, in the cerebral peduncle medial to the corticospinal tract (blue); 2) lateral mesencephalic sulcus, posterior to the cerebral crus; 3) intercollicular, in the tectal midline; 4) suprafacial colliculus, lateral to the median sulcus and medial longitudinal fasciculus and superior to the facial nucleus; 5) lateral pontine, through the middle cerebellar peduncle; 6) olivary, into the pontomedullary sulcus through the upper portion of the olive; 7) posterior lateral sulcus, lateral to the cuneate fasciculus; 8) posterior intermediate sulcus, between the gracile and cuneate fasciculi; and 9) infrafacial colliculus, inferior to the facial nucleus and superior to the stria medullaris and calamus scriptorius (hypoglossal triangle, vagal triangle, and area postrema). Used with permission from Barrow Neurological Institute, Phoenix, Arizona.

TABLE 1. Characteristics of fourth-generation bypasses compared to other bypasses

Bypass	Seven Bypasses No.	Generation (type)	No. of Anastomoses	Anastomosis	Technique
EC-IC bypass	1	1	1	E-S	Conventional
EC-IC interpositional bypass	2	2	2	E-S, E-E	Conventional
Reimplantation	3	3	1	E-S	Conventional
		4A	1	E-S	In situ
		4B	1	E-E	Conventional or in situ
		4B	1	S-S	In situ
In situ bypass	4	3	1	S-S	In situ
Reanastomosis	5	3	1	E-E	Conventional
		4A	1	E-E	In situ
		4B	1	E-S	Conventional or in situ
		4B	1	S-S	Conventional or in situ
IC-IC interpositional bypass	6	3	2	E-S, E-E	Conventional
		4A	2	E-S, E-E	In situ
		4B	2	S-S	In situ
Combination bypass	7	3	≥2	E-S, S-S, E-S	Conventional or in situ

E-E = end to end; E-S = end to side; S-S = side to side.

surgical patients with low-grade AVMs (Spetzler-Martin grades I and II), complete resection was achieved in all patients with no mortality, and 97% of patients had improved or unchanged neurological outcomes.⁴⁸ These results justify microsurgery as first-line therapy for most low-grade AVMs, utilizing embolization as a preoperative adjunct and radiosurgery for AVMs in deep, inaccessible, and eloquent locations.

On the Defensive

Management of AVMs in other parts of the world is diverging from the above surgical approach. In Europe, for example, treatment is limited to ruptured AVMs, which begins with embolization, then the frequent addition of stereotactic radiosurgery for incompletely embolized AVMs, rarely resorting to resection.⁴⁶ Endovascular cure rates are rising with the use of Onyx and novel methods such as the “pressure cooker” technique and transvenous embolization.⁴² In a review of 1297 patients with mostly low-grade AVMs, the average endovascular morbidity and mortality rates were 6.2% and 1.6%, respectively, with an average cure rate of 29% and a postoperative or delayed hemorrhage rate of 8.0%.⁴⁸ Therefore, current endovascular therapy has higher procedural risks, lower cure rates, and higher hemorrhage risks than those with microsurgery. Similarly, in a review of 1051 patients with low-grade AVMs treated with radiosurgery, 7.2% of patients hemorrhaged after treatment, resulting in morbidity and mortality rates of 6.5% and 1.2%, respectively.⁴⁸ The 75.2% radiosurgical cure rate was substantially better than the endovascular cure rate but still less than that of microsurgery. Despite advances in endovascular and radiosurgical therapy, microsurgery still offers the best cure rate, lowest risk profile, and greatest protection against hemorrhage for low-grade AVMs.⁴⁸ Surgery cannot compete with the minimally invasive appeal of other modalities, but this appeal is, and should remain, secondary to functional outcome.

ARUBA and Its Aftermath

Microsurgery has also been challenged by medical management. In ARUBA, the first randomized trial of unruptured AVMs, 109 patients assigned to medical management were compared to 114 patients assigned to interventional therapy of embolization, radiosurgery, microsurgery, or a combination.⁴⁰ During 33 months of follow-up, 30.7% of patients in the interventional arm had a stroke or died compared with only 10.1% in the medical arm. In addition, 46.2% of patients in the interventional arm were impaired (modified Rankin Scale score of 2 or higher), compared with 15.1% in the medical arm. Thus, unruptured AVM patients in the medical group had a significantly lower risk of death or stroke and better outcomes than patients in the treatment group, calling into question any intervention for unruptured AVMs.

The natural progression of healthcare is to develop sophisticated ways of treating pathology without bodily invasion. However, when open microsurgery offers the highest cure rate, lowest complication rate, excellent outcomes, and immediacy, it must be vigorously preserved. Critics of ARUBA highlighted the trial’s nonsurgical management of patients in the interventional group: only 17 patients (18%) were treated surgically, with or without embolization, and the rest (81%) were treated with embolization alone (32%), radiosurgery alone (33%), or embolization and radiosurgery combined (16%).^{19,40} Critics analyzed ARUBA-eligible patients managed outside the trial.^{58,70} As an ARUBA participant who screened 473 patients for eligibility and enrolled only 4, I and my team had complete data on 74 eligible patients managed outside the trial.⁵⁶ Of the 61 patients receiving intervention, 43 (71%) were treated surgically with or without preoperative embolization and 15 (25%) were treated radiosurgically; 13 (18%) were observed. Of the remaining 3 patients, 1 had embolization alone and 2 had multimodal treatment with embolization, surgery, and radiosurgery. The risk of stroke and death and

FIG. 4. AVM taxonomy. Although size, shape, and location make AVMs infinitely variable and unique, 32 anatomical categories exist based on their 7 locations, 1) frontal lobe, 2) deep (basal ganglia and thalamus), 3) parieto-occipital lobes, 4) periventricular/ventricular, 5) temporal lobes, 6) brainstem, and 7) cerebellum, and on the brain surface on which they are based (e.g., lateral, medial, basal, Sylvian, and paramedian surfaces in the frontal lobe). Like genus and species that characterize animals, AVM type (location) and subtype (surface) characterize AVMs in a taxonomy that deciphers pathological anatomy and defines surgical strategy. Large center image is used with permission from Barrow Neurological Institute, Phoenix, Arizona. Parts 1–7 are from Lawton MT: *Seven AVMs: Tenets and Techniques for Resection*, Thieme, 2014 (reprinted with permission).

TABLE 2. Literature review of fourth-generation bypasses

Type	Authors & Year	Age (yrs)/Sex	Pathology	Aneurysm Treatment	Bypass
Reanastomosis	Lee & Choi, 2015	74/F	L distal PICA dissecting aneurysm	Trapping	L p2 PICA (S-S) L p3 PICA
Reimplantation	Benes et al., 2006	65/F	L giant partially thrombosed VA aneurysm	Trapping	L V4 VA (E-E) L p1 PICA
	Matsushima et al., 2011	69/F	L PcaA-CmaA junction aneurysm	Trapping	L PcaA (E-E) L CmaA
	Lee et al., 2017	47/F	L A3 ACA (PcaA) pseudoaneurysm distal to CmaA origin	Trapping	L CmaA (S-S) L A4 ACA
	Lee et al., 2018	47/F	A3 ACA pseudoaneurysm	Trapping	PcaA (S-S) CmaA*
Multiple reimplantations	Sekhar et al., 2005	51/F	Aneurysm at previous ATA-MCA reimplantation site	Excision	R M2 MCA (S-E) SthG [(S-E) M3 MCA + (E-E) M3' MCA]†
	Nakajima et al., 2012	23/F	R MCA bifurcation complex aneurysm involving 3 M2 MCA branches & a perforator	Excision	R STA (E-S) R M2 MCA + R STA' [(S-E) M2' MCA + (E-S) M2" MCA] + R M2' MCA (E-S) Perf.
	Kato et al., 2013	41/F	R MCA trifurcation giant aneurysm	Trapping	R ECA (S-E) SVG [(S-E) R M2 MCA + (S-E) R M2' MCA + (E-S) R M2" MCA]
		67/M	R MCA giant aneurysm	Trapping	R ECA (S-E) SVG [(S-E) R M2 MCA + (E-S) R M2' MCA]
	Arnone et al., 2019	59/M	Bilat ICA occlusion + L M1 MCA occlusion + 50% L VA stenosis	NA	L STA [(S-S) L M4 MCA + (E-S) L M4' MCA]‡

A3 ACA = third segment of anterior cerebral artery; A4 ACA = fourth segment of ACA; ATA = anterior temporal artery; CmaA = callosomarginal artery; L = left; M1 MCA = first segment of MCA; M3 MCA = third segment of MCA; NA = not applicable; p1 PICA = first segment of PICA; p2 PICA = second segment of PICA; p3 PICA = third segment of PICA; PcaA = pericallosal artery; Perf. = perforating artery; R = right; SthG = superior thyroid artery graft; SVG = saphenous vein graft; VA = vertebral artery.

* Incomplete trapping. Donor and recipient are on the same side. Side not specified.

† M2, M2', and M2" signify different MCA trunks. Similarly, STA and STA' denote different post-bifurcation STA trunks.

‡ The L STA (E-S) L M4'-MCA anastomosis was done with an in situ technique so it is considered both type 4A and 4B.

the degree of clinical impairment among treated patients was lower than those in ARUBA, with primary outcome rates of 11%, 27%, and 8% for microsurgery, radiosurgery, and observation, respectively. ARUBA's threefold difference in primary outcome disappeared with different management and surgical expertise, leaving no significant difference in outcome between treated and observed patients.⁴⁰ Other centers reported similar results, validating the primary role of microsurgery, judicious surgery selection with established outcome predictors, and technical expertise developed at high-volume AVM centers.^{20,45}

Although ARUBA's impact on AVM microsurgery has been modest (Fig. 1), it may have increased clinician and patient awareness of interventional morbidity, which may have helped to regionalize AVM surgery in centers of excellence.¹⁰ Defending this therapeutic option is more than a point of pride and cause for optimism. A therapy with high cure rates and excellent functional outcomes in both ruptured and unruptured AVM patients must be protected. Novel alternatives must demonstrate efficacies and outcomes that match or exceed the microsurgical benchmarks before they replace current microsurgical therapy.

Innovating Open Microsurgery: Complex Aneurysms and Bypass

Decline of Aneurysm Surgery

Unlike the trends for CCMs and AVMs, those for aneurysms are alarming (Fig. 1). It is disheartening to have

climbed learning curves, mastered skills, published extensively, written textbooks, and developed my reputation in the field, only to have a shrinking practice.^{21,22} Technology, infiltration from other disciplines, and market forces are overwhelming. Simple aneurysms are treated endovascularly with stand-alone coiling, balloon-assisted coiling, and stent-assisted coiling. Flow diverters now dominate the treatment of cavernous and paraclinoid internal carotid artery (ICA) aneurysms, and off-label use extends beyond the supraclinoid ICA.^{15,61} Intra-aneurysmal flow diverters have been developed for bifurcation aneurysms.³ What remains for microsurgery are complex aneurysms, defined as those with wide necks, large size, dolichoectatic morphology, intraluminal thrombus, previous endovascular therapy, or atherosclerotic walls.^{26,31,38} This portion of the aneurysm market demands even more from vascular neurosurgeons, increasing the need for bypasses (Fig. 1). Bypass surgery is a growth area, inspiring innovation, creativity, and expressivity.

Three Generations of Bypasses

Bypass surgery can be viewed evolutionarily in generations (Supplementary Table 3).²⁴ The superficial temporal artery–middle cerebral artery (STA-MCA) bypass developed and popularized by Yaşargil and Donaghy in the late 1960s remains the most common, versatile, and simple extracranial-intracranial (EC-IC) bypass, with applications to aneurysms, moyamoya disease, intracranial atherosclerosis, and carotid occlusion.⁷¹ Its end-to-side

anastomosis on the cerebral convexity is a basic construct with excellent results. Bypasses between scalp arteries and cortical recipients are first-generation bypasses, but their limited blood flow led to the development of second-generation EC-IC interpositional bypasses, championed by Sundt, from cervical carotid donors to replace blood flow after deliberate sacrifice.⁶³ These EC-IC interpositional bypasses use the same end-to-side anastomoses, but an interpositional graft connected to the carotid artery doubles the bypass flow. Interpositional bypasses require additional harvest and donor sites, a tunnel, and a second anastomosis, and technical skills to join donors, recipients, and grafts of different calibers.⁵⁰

The third-generation bypasses are intracranial reconstructions that reanastomose parent arteries, reimplant efferent branches, revascularize efferent branches with in situ donor arteries, and reconstruct bifurcated anatomy with interpositional grafts.^{51,53,57} Reimplantation joins an efferent branch deliberately detached from an aneurysm to an adjacent artery with an end-to-side anastomosis, drawing intracranial flow from an adjacent bystander artery or a preserved efferent branch from the aneurysm. In situ bypass joins donor and recipient arteries that run parallel and in proximity to one another with a side-to-side “one way up” anastomosis that eliminates the need for arterial mobility. Like reimplantation, in situ bypass implicates a bystander artery not involved with the pathology as a donor, subjecting its territory to cross-clamping, possible ischemic injury, and complications if the anastomosis occludes.

Reanastomosis rejoins transected ends of afferent and efferent arteries after excising aneurysmal pathology to reconstruct parent artery anatomy and restore flow, but excision of large or giant aneurysms leaves a gap that can be difficult to close. Reanastomosis requires slack on the cut ends to bring them together without tension. Sometimes the tension on transected arterial ends can be too great for reanastomosis, or the donor is just out of reach for reimplantation or in situ bypass. The IC-IC interpositional bypass is the remedy, connecting two arteries with a graft and two anastomoses, making IC-IC interpositional bypasses shorter in length, smaller in caliber, perfect for radial artery grafts, protected intracranially from external trauma, and sparing a second surgical exposure and a tunnel.⁶⁴

Seven Bypasses

Bypasses can be categorized by the 3 generations, 7 variations (Supplementary Table 3), and 4 anatomical locations.²⁴ For complex aneurysms, we must often invent new bypasses, reengineer hemodynamics, and imagine solutions to complex diseases, such as the dolichoectatic basilar aneurysm, that are considered hopelessly incurable.^{2,26} In architecture, a structure is built only if the design conceived in the architect’s mind is captured on blueprints for the construction crew. Just as symbols for floor plans, fixtures, and infrastructure (e.g., wiring and plumbing) translate the architect’s vision into a building plan, symbols for bypass surgery now translate the neurosurgeon’s ideas into bypass types, techniques, and grafts, depicting the aneurysm surgery. A precise alphanumeric language based on the segmental anatomy of arteries encodes the bypasses and improves the discourse. With these alpha-

numeric symbols and “blueprints” specifying anastomotic sites and techniques, we can transform the practice of bypass surgery from plumbing to art.⁵⁴ For example, anterior inferior cerebellar artery (AICA) bypasses were so few that I did not include the cerebellopontine cistern as a key bypass location in *Seven Bypasses*.²⁴ Since then, all 7 bypasses (Supplementary Table 3) have been performed in the cerebellopontine cistern (Fig. 5), including a p3 PICA-a3 AICA in situ bypass for a giant, thrombotic AICA aneurysm (Fig. 6) and a deep a2 AICA reanastomosis just lateral to the abducens nerve. These AICA bypasses exemplify innovation and progress in bypass surgery. Bypass surgery is the new state of the art in open vascular neurosurgery, and with imagination and forethought, it will likely evolve into an elegant and artistic collection of nuanced techniques and skills.

Evolving Open Microsurgery: Fourth-Generation Bypass

Double Reimplantation Technique

The double reimplantation bypass helped me recognize the fourth generation of bypasses. This bypass is a second-generation interpositional bypass with reimplantations of 2 efferent branches onto a graft connected proximally to the carotid artery (3 end-to-side anastomoses), rebuilding an arterial bifurcation and trapping the aneurysm.³⁰

The double reimplantation technique evolved into a third-generation bypass when A1 ACA was used as an intracranial donor site instead of the external carotid artery (ECA).⁷ The elements of this IC-IC double reimplantation are the same as those of the EC-IC, with proximal end-to-side anastomosis of the graft to the donor artery first, reimplanting the first efferent trunk onto the graft with another end-to-side anastomosis, and reperfusion of the reimplanted artery immediately. With the increasing use of the middle cerebral artery (MCA) double reimplantation technique (A1 ACA-RAG-M2 MCA + M2 MCA), I found the frontal trunk could be revascularized with side-to-side anastomosis between the graft and efferent trunk more easily than reimplanting it with end-to-side anastomosis (Fig. 7). The lenticulostriate arteries arising from the trunk limit its mobility, and a more distal side-to-side anastomosis protects these perforators. Side-to-side anastomosis keeps the efferent trunk in its natural position instead of mobilizing it to the graft, and the mobile graft easily reaches the optimal anastomotic site on the efferent trunk. Should this first bypass be considered a reimplantation or an in situ bypass? Additionally, I found that the temporal trunk could be revascularized with a shorter graft if the end-to-side anastomosis was performed using an in situ technique, with the first suture line sewn intraluminally with entrance and exit stitches on either end but with the same end-to-side construct. Should this second bypass be considered a reimplantation or an in situ bypass?

Type 4A and 4B Bypasses

What began as a second-generation double reimplantation technique transformed into a third-generation bypass, and with side-to-side reimplantation of the frontal trunk onto the graft and end-to-side reimplantation of the tem-

FIG. 5. AICA bypasses are so rare that when *Seven Bypasses* was written, they were barely mentioned, and the cerebellopontine cistern was not included as a key bypass location.²⁴ Since then, all 7 bypasses have been performed, exemplifying the innovation and progress in bypass surgery: 1) OA-a3 AICA bypass for bilateral vertebral artery (VA) occlusions and vertebrobasilar ischemia; 2) OA-RAG-a3 AICA interpositional bypass for bilateral VA occlusions and vertebrobasilar ischemia, with OA damage during harvest; 3) a2 AICA reimplantation onto V4 VA with a side-to-side anastomosis before clipping a proximal basilar trunk aneurysm that may occlude the AICA at its origin; 4) p3 PICA-a3 AICA in situ bypass to trap and thrombectomize a fusiform a2 AICA aneurysm compressing the pons (*inset* shows reanastomosis); 5) excision and reanastomosis of a ruptured, mycotic a2 AICA aneurysm; 6) V3 VA-SVG-a3 AICA interpositional bypass performed for bilateral VA occlusions and two pontine strokes managed medically; and 7) combination bypass (left OA-a3 AICA bypass and excision/reanastomosis of a right p3 PICA aneurysm [*inset* shows reanastomosis]) performed through a left far lateral–retrosigmoid craniotomy in a patient who also had a thrombotic, dolichoectatic basilar trunk aneurysm that was treated with flow diversion. Elegant bypasses will redefine bypass surgery and expand the management of complex aneurysms. a2 AICA = second segment of AICA; a3 AICA = third segment of AICA; an or An = aneurysm; BA = basilar artery; L. = left; OA = occipital artery; p3 PICA = third segment of PICA; R. = right; RAG = radial artery graft; SVG = saphenous vein graft; V3 VA = third segment of VA; V4 VA = fourth segment of VA; VBJ = vertebrobasilar junction. Used with permission from Barrow Neurological Institute, Phoenix, Arizona.

FIG. 6. Case 1. p3 PICA-a3 AICA in situ bypass. A 75-year-old woman presented with headaches, imbalance, dyscoordination, and left hemiparesis from a fusiform, thrombotic right AICA aneurysm compressing the pons. **A:** Axial T1-weighted MR image showing pontine edema and the extent of aneurysm thrombosis in this large aneurysm. **B:** Right VA angiogram, anteroposterior view. AICA bypass, aneurysm trapping, and thrombectomy were indicated to relieve mass effect, but the OA was too diminutive for OA-a3 AICA bypass. **C:** p3 PICA and a3 AICA coursed parallel and in proximity to each other and could be approximated for a side-to-side anastomosis (intraoperative view through a retrosigmoid craniotomy). **D:** After making linear arteriotomies in the donor and recipient arteries, their two inner walls were joined with a continuous suture line. The second suture line joined their outer walls and completed the anastomosis. **E and F:** Low- and high-magnification views. **G:** With the PICA now supplying the distal AICA territory, the aneurysm was trapped with aneurysm clips, incised between the trigeminal nerve superiorly and the vestibulocochlear nerves inferiorly, and thrombectomized. Note the abducens nerve below the vestibulocochlear nerves. **H:** Right VA angiogram, lateral view, demonstrates a patent bypass with supply of both the PICA (P) and AICA (A) territories. The patient's symptoms resolved completely, and she had an excellent outcome at 6 months. This case demonstrates the application of established bypass techniques in novel ways to advance the art of bypass surgery. Used with permission from Barrow Neurological Institute, Phoenix, Arizona.

FIG. 7. Case 2. A1 ACA-SVG-M2 MCA + M2 MCA double reimplantation bypass (fourth generation, type 4A and 4B). A 70-year-old man presented with mild left-sided weakness due to an embolic stroke from a giant right MCA bifurcation aneurysm. Axial CT angiogram (A) and right ICA angiogram (B), anteroposterior view. The aneurysm was exposed (C) through a right orbito-pterional craniotomy and transsylvian approach; dolichoectatic morphology plus a giant size prevented direct clipping. The A1 ACA served as the intracranial donor and the SVG (an SVG was used because the radial artery was not available) was arterialized with an end-to-side anastomosis. The superior trunk was reimplanted using linear arteriotomies on the graft and the trunk and running intraluminal sutures to join their inner walls (D). The outer walls were closed to complete this side-to-side reimplantation (type 4B, E). **FIG. 7. (continued)**→

FIG. 7. The in situ technique was used again for reimplantation of the inferior trunk, sewing the back wall of this end-to-side anastomosis intraluminally and completing the front wall extraluminally (type 4A, F). The in situ technique kept the graft stationary and enabled shorter trimming. The aneurysm was trapped with clips, suction decompressed, and clipped finally to preserve a lenticulostriate artery at the base of the aneurysm between the afferent M1 MCA and the origin of the superior trunk (G). Postoperative right ICA angiogram, lateral view (H), confirming robust bypass flow and complete aneurysm exclusion. The patient was discharged without new neurological deficits. This case demonstrates both types of fourth-generation bypasses: a side-to-side reimplantation of the frontal trunk (unconventional structure created with conventional suturing technique) and an in situ reimplantation of the temporal trunk (conventional structure with unconventional suturing technique). A1 ACA = first segment of anterior cerebral artery; CN2 = cranial nerve II; InfTr = inferior trunk; M1 MCA = first segment of MCA; M2 MCA = second segment of middle cerebral artery; SupTr = superior trunk. From Lawton MT: *Seven Bypasses: Tenets and Techniques for Revascularization*, Thieme, 2018 (reprinted with permission).

poral trunk via an in situ technique, it transformed into a fourth-generation bypass. This bypass demonstrates two types of fourth-generation bypass (Fig. 8). In type 4A, the construct is the same as in the third-generation bypass (end-to-side or end-to-end anastomosis), but an in situ suturing technique is used (no actual side-to-side anastomosis). In other words, the type 4A bypass maintains conventional structure with an unconventional suturing technique. In type 4B, the basics of reimplantation (reattaching an efferent artery to a parent or adjacent artery) or reanastomosis (joining afferent and efferent arteries) remain, but the anastomosis changes to another anastomosis. In other words, the type 4B bypass has an unconventional structure and is created with either a conventional or an unconventional suturing technique.

This conceptualization generates 8 new fourth-generation bypasses: 3 reimplantation bypasses, 3 reanastomosis bypasses, and 2 interpositional bypasses (Table 1). Third-generation (type 3) reimplantations incorporate an end-to-side anastomosis with conventional fish-mouthed arteriotomy and extraluminal suturing, whereas fourth-generation reimplantations are performed with an end-to-side anastomosis and the in situ technique (type 4A) or with an end-to-end or side-to-side anastomosis (type 4B). The type 4A reanastomosis is constructed with the same end-to-end anastomosis as a third-generation reanastomosis, except that the first suture line is sewn intraluminally, usually because the arterial gap does not enable the arterial ends to rotate for traditional extraluminal suturing. Type 4B reanastomosis brings the afferent and efferent arteries of an aneurysm together with an end-to-side or side-to-side anastomosis rather than the conventional end-to-end anastomosis. Finally, the third-generation interpositional bypass that uses end-to-side or end-to-end anastomoses to connect the interpositional graft to donors and recipients becomes a type 4A bypass when the in situ technique is used to complete either of these two anastomoses, and it becomes a type 4B bypass when a side-to-side anastomosis is used to connect the graft to donor or recipient.

During a 21-year period in which I performed 605 cerebral bypasses, complex aneurysms were the most common indication (254 cases [42%]), and aneurysm recurrence after endovascular therapy accounted for 11% (28 cases) of these. Of the 4479 aneurysms treated microsurgically in 3313 patients, bypass was a part of the treatment in 7.7% (254 cases) of aneurysm patients (Fig. 1). Of the 181 IC-IC bypasses, 34 (19%) were fourth-generation bypasses.⁷² Of these fourth-generation bypasses (34 cases), 27 (79%) were type 4A, including 8 in situ reimplantations, 7 in situ reanastomoses, and 12 in situ interpositional bypasses. There were 7 type 4B bypasses (21%), with side-to-side

reimplantation of an arterial trunk in 5 cases as part of the MCA double reimplantation bypass. Although the number of cases is small, defining fourth-generation bypass demonstrates the evolution of vascular neurosurgery. When the literature was reviewed, other examples of fourth-generation bypass were found (Table 2).^{4,6,19,33–35,39,43,60} The application of sophisticated bypass techniques to address complex aneurysms is the bright spot in the shrinking aneurysm market.

Perspective on the Future

If faced with the same career decision in today's practice environment, would I make the same choice I made 25 years ago? Evolution in the treatment of brainstem CCMs demonstrates that fresh insights and the application of open microsurgical skills can expand vascular neurosurgery. Experience with AVMs demonstrates that even as other modalities advance to minimize invasive interventions, occlusive and obliterative therapies remain inferior to resective therapies. Experience with aneurysms demonstrates that open microsurgery may be superior to endovascular therapies in patients with complex aneurysms, reconfirming the need for open vascular neurosurgeons.⁹ Therefore, I foresee a lasting role for open microsurgery in vascular neurosurgery, and I would choose to enter the specialty again, with training in both open microsurgical and endovascular techniques. Indeed, I completed an endovascular fellowship in 2011 even after establishing a thriving academic vascular neurosurgical practice.

The ability to catheterize arteries and veins provides incredible access to pathology and multiplies our therapeutic power. Furthermore, this area is bursting with innovation and excitement.⁵⁵ The endovascular culture is filled with pioneers, cutting-edge technology, and minimally invasive opportunities, which makes it more seductive than the microvascular culture. Nonetheless, open microsurgery is and should remain a cornerstone of neurosurgical culture because it offers anatomical insights and contact with pathology that is difficult to get from radiography alone. Instruments under the microscope respond to the hands with perfect precision, and we cannot relinquish this power. Our very best neurosurgeons must be capable of repairing the complex lesions that cannot be managed any other way.

Case volume is the secret of success because it develops experience, efficiency, and confidence. Aneurysm surgeons covet case volume, make personal sacrifices to acquire it, and endure its side effects.²⁷ Microsurgical aneurysm volume is being concentrated with fewer experts, and employment opportunities will be scarce in the future.¹⁸ Consequently, choosing a career in microvascular surgery will

FIG. 8. Fourth-generation bypasses. Bypasses needed to manage complex aneurysms have been conceptualized into 7 categories: 1) EC-IC bypass; 2) EC-IC interpositional bypass; 3) reimplantation; 4) reanastomosis; 5) in situ bypass; 6) IC-IC interpositional bypass; and 7) combination bypass. When conventional combinations of anastomoses and techniques are reshuffled, a fourth generation of bypasses results in 8 new types of bypasses. For example, the 2 efferent trunks of a complex right MCA aneurysm (*top row, left*) can be treated with trapping and a combination bypass (STA-MCA bypass plus end-to-side reimplantation; type 3; *second row, left*). **FIG. 8.** (*continued*)→

FIG. 8. Alternatives to this third-generation approach include the same end-to-side reimplantation with in situ technique (type 4A; *third row, left*) or either side-to-side reimplantation or end-to-end reimplantation (type 4B; *fourth and fifth rows, left*). A fusiform PICA aneurysm (*top row, center*) can be treated with excision and end-to-end reanastomosis (type 3; *second row, center*). Alternatives to this third-generation approach include the same end-to-end reanastomosis with in situ technique (type 4A; *third row, center*) or either side-to-side reanastomosis or end-to-side reanastomosis (type 4B; *fourth and fifth rows, center*). Finally, the 2 efferent trunks of a complex right MCA aneurysm (*top row, right*) can be treated with trapping and interpositional bypass (double reimplantation; type 3; *second row, right*). Alternatives to this third-generation approach include the same end-to-side reimplantation with in situ technique (type 4A; *third row, right*) or either side-to-side reimplantation or end-to-end reimplantation (type 4B; *fourth and fifth rows, right*). An = aneurysm; M2 = second segment of MCA; p3 = third segment of PICA. Used with permission from Barrow Neurological Institute, Phoenix, Arizona.

become a competitive pyramid. With 218 graduates from neurosurgical residency programs annually and approximately 10 accredited open vascular fellowships, the likelihood of a resident becoming a microvascular surgeon is approximately 4.6%.⁶² That success rate is high relative to that for major league baseball, for example. The overall probability of a high school athlete becoming a professional in major league baseball is 0.015%.⁴⁴ Entrance into open vascular neurosurgery may not ever be this extreme, but the rate will likely fall sharply with continued endovascular advancements. Therefore, those who embark on this career path must accept intense competition and the possibility of being culled. Aspiring neurosurgeons will face a choice between chasing their passion with a high attrition rate or opting for a more accepting alternative. Survivors of this pyramidal system will presumably be the best selections for the specialty, and those who were culled will have invaluable microsurgical skills for their alternative pursuits.

Surviving a harsh cut may still not be enough to succeed in future microvascular practice. Today, a thriving microvascular practice requires subspecialization, a collaborative team of endovascular surgeons and vascular neurologists, supportive neurosurgical partners, an academic medical center, regional prominence, and a large catchment population. Microvascular neurosurgeons will also need a health system that funnels patients from a network of hospitals outside the region. The high-volume hospitals (top 20% by case volume) perform 60% of neurosurgical cases (S. Yoon et al., unpublished data, 2018).⁶⁵ After adjustments for patient morbidity and case complexity, these centers were 4.3% less expensive, and transferring 10% of patients from low-volume hospitals to high-volume hospitals would have saved about \$192 million annually.¹¹ These economic attributes will drive the future regionalization of microsurgery. Ironically, the future is moving back to the days of Charles Drake when patients with a lesion like a vertebrobasilar aneurysm were referred to a designated center of excellence where committed neurosurgeons gained expertise and made therapeutic advancements.¹² Consolidation of health systems, bundled services, published outcome metrics, advancing technology, political reform, and mass marketing will likely stimulate this reformulation of neurosurgical care. Attracting patients and securing case volume has become so challenging that it is no longer possible to rely on neurosurgical prowess and reputation.

Those of us committed to open microsurgery believe that manual dexterity and technical skills still matter. It is ironic that the anastomoses that have existed for decades produce some of neurosurgery's most artful constructs and that we resort to old-fashioned techniques when cutting-edge devices fail. Modern neurosurgery has been shaped by endovascular technology, radiosurgery,

endoscopy, minimally invasive techniques, and biological therapies that may be completely noninvasive. Neurosurgical procedures are being reduced to burr holes, frame placements, needle biopsies, and catheter manipulations. Microvascular surgery stands against these trends by requiring a few simple instruments, steady hands, and meticulous technique. Dexterity remains the magic that makes microsurgery happen. However, the mastery of a vascular neurosurgeon comes from the head and the heart—thinking through the right strategy and best solution and then striving to achieve perfection. The art of neurosurgery will evolve if enough of us continue to engage our hands, heads, and hearts in the treatment of our most complex and difficult lesions. I foresee a bright and artful future where a cadre of creative surgeons perpetuate this beautiful craft of open microsurgery.

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Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.

Supplementary Tables 1–3. <https://thejns.org/doi/suppl/10.3171/2019.1.JNS182156>.

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