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REVIEW

The *re-anastomosis* end-to-end bypass technique: a comprehensive review of the technical characteristics and surgical experience

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Abstract
Re-anastomosis end-to-end bypass is a straightforward subtype of intracranial-intracranial reconstruction technique that has been utilized to treat complex aneurysms and skull base tumors. This simple technique involves connecting the cut ends of an afferent and efferent artery under added tension after excising the lesion. The current study aims to provide a detailed description of the technical pitfalls, ideal anatomical sites and indications, and clinical outcomes for intracranial complex disorders. A literature search was performed using the terms "intracranial-intracranial bypass," "re-anastomosis bypass," "reconstructive bypass," "end-to-end bypass," and "end-to-end anastomosis" to identify pertinent articles. Articles involving end-to-end re-anastomosis combined with other bypass methods were excluded. Computer-tablet-drawn illustrations of this technique are provided to enhance comprehension. Eighty-six patients who met our search and inclusion criteria were identified between 1978 and the present. However, comprehensive descriptions of medical records and neuroimaging were available in only 41 cases (40 complex aneurysms and a skull base tumor). Of 40 reported cases of complex cerebral aneurysms treated by this technique, the overall rate of full recovery without complication is 87.5% (35/40). Meanwhile, all aneurysms were completely eliminated from the circulation, with 92.5% of bypasses being patent. End-to-end re-anastomosis remains a simple modality in the microsurgical bypass armamentarium. Safe and effective surgical outcomes can be achieved in select cases that rarely involve perforators or branches.

Keywords Complex intracranial aneurysm · End-to-end anastomosis · End-to-end bypass · Intracranial-intracranial bypass · Re-anastomosis bypass · Reconstructive bypass

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Introduction

The intracranial-intracranial (IC-IC) bypass technique has gained momentum in the last several years because it is simpler and less invasive than many other approaches for arterial reconstruction [10, 32, 42, 50–55]. This technique is commonly categorized into four patterns: re-anastomosis in an end-to-end (ETE) fashion, in situ bypass in a side-to-side (STS) fashion, re-implantation bypass in an end-to-side fashion, and interpositional bypass using a graft vessel [10, 28, 42]. Of those four types, the re-anastomosis ETE bypass is frequently used following an aneurysmal pathology excision or a tumor resection [19]. This technique was performed to detach the parent artery by re-joining transected ends of inflow and outflow arteries to restore the continuity original blood flow without introducing a graft vessel or new input [1, 2, 10, 21, 27, 41, 42]. Flow in the recipient artery of a reconstructive bypass is exactly the same as before [21]. Re-anastomosis requires a suture line that is shorter than other IC-IC reconstruction subtypes, and fewer anastomosis bites need to be performed, making it quicker than other methods [2, 21, 28, 39, 42]. Meanwhile, this anastomosis modality reconstructs the arterial anatomy in the most similar possible form to the original geometry of the vessel with matched calibers of afferent and efferent arteries [21, 27]. In addition, ETE anastomosis is less technically challenging due to the visualization of translucent arterial walls and both suture lines [39, 42].

Several technical considerations are required to successfully accomplish re-anastomosis bypass. ETE reconstruction is critically dependent on the tortuosity and redundancy of the parent artery, where older people have more length than the adolescent counterpart due to arterial elongations [1, 2, 21, 28, 56]. Extensive dissection to slack and mobilize vascular stumps is required to free mechanical tension by releasing arachnoid adhesions, detethering insignificant twigs, and thrombectomizing and debulking a large or giant aneurysm [21, 37, 42, 56]. If the tension is too great when tightening stitches, knots cannot approximate the cut ends, which may induce sutures to pull out from the walls or breakage, tearing through the artery wall, insufficient rotation of arteries, ruining the repair, and costly trimming of the additional vessel tissue [21, 27, 28, 51]. It should be noted that a tense suture line could narrow the anastomosis and contribute to graft occlusion. Furthermore, a bridgeable arterial gap between proximal and distal stumps of the arteries is measured as less than 10 mm, allowing for both stumps to meet [19, 27, 49]. However, Al-Khayat and Kopitnik [3] performed a direct re-anastomosis after resecting a 2-cm diseased segment of the artery. In addition, re-anastomosis bypass should be safely carried out at sites without disrupting any critical branches or perforators [5, 56]. Lastly, ETE anastomosis requires thorough excision of all abnormal arterial tissues, including aneurysm, weakened or thrombogenic tissue, and back to the normal portion of the donor and recipient vessel to avoid ceased blood flow [21, 27, 28, 31, 42, 56]. Any retained pathology at the transected ends will doom the bypass [21, 28, 38]. At the same time, however, aggressive resection might make a gap unbridgeable and prevent arterial ends from reconnecting [21, 28]. Therefore, careful intraoperative assessment of vascular and lesion anatomy is critical before attempting ETE reconstruction to ensure a high likelihood of success [27, 28].

Although IC-IC bypass has gained increasing attention, published studies regarding ETE subtypes are rare or inconsistent. In addition, studies performing a general assessment of this technique remain scarce. The aim of this study is to retrospectively review the comprehensive information regarding the technical characteristics and surgical outcomes of ETE reconstruction for complex aneurysms and skull base tumors.

Materials and methods

A comprehensive review of the English-language published literature was performed by searching the PubMed, Medline, ScienceDirect, Cambridge Journals, SAGE Journals, Oxford Journals, Embase, Wiley Online Library, Research Gate, and Google Scholar databases. The terms "intracranial-intracranial bypass," "re-anastomosis bypass," "reconstructive bypass," "end-to-end bypass," and "end-to-end anastomosis" were used to search for pertinent articles. Studies involving re-anastomosis ETE revascularization combined with other bypass methods (EC-IC or IC-IC), animal studies, cadaver studies, technique assessments, in vitro training studies, and studies published in languages other than English were not included in this analysis. Any studies published in non-scholarly journals or articles with a high likelihood of bias or conflicting data were excluded to ensure a high-quality review. Computer-tablet-drawn illustrations of re-anastomosis ETE bypass are provided to enhance comprehension of this technique in various situations. The simplified illustrations were created by the junior author (L.C.).

Results

Forty-eight pertinent articles were identified in the literature, including 19 case reports, 26 original articles, and 3 surgical videos. Eighty-six cases were included between 1978 and the present. Since, Dolenc [11] described the first case of aneurysmal excision and re-anastomosis for a complex MCA aneurysm. However, comprehensive descriptions of medical record and surgical outcomes were achieved in 41 cases (40 complex aneurysms and a skull base tumor). Of 40 reported cases of complex cerebral aneurysms treated with this technique, the overall rate of full recovery without complication is 87.5% (35/40). When reported, the rate of vessel patency following re-anastomosis is high (92.5%; 37/40) with 100% elimination of aneurysm. (Table 1).

Complications

Of the five patients with unfavorable outcomes, one was in the territory of ACA, three in MCA, and one in PICA. A patient with the PICA aneurysm that presented with a poor-grade aSAH died due to the bypass occlusion and subsequent cerebrovascular accident. Two other patients experienced surgical-related complications following the detection of graft occlusion. One patient presented with a giant MCA aneurysm died by the virtue of ischemic deficits after prolonged temporary clipping. Another patient with a giant serpentine MCA aneurysm found fronto-insular area ischemia in spite of patent graft

Table 1 Summary of re-anastomosis bypasses for complex aneurysms

Aneurysm location	Case No.	Aneurysm characteristics	Patency rate	Aneurysm obliteration rate	Independent outcomes
ACA	7	Giant, thrombosed, fusiform, dissecting, thrombotic	85.7% (6/7)	100% (7/7)	85.7% (6/7)
MCA	16	Giant, thrombosed, fusiform, dolichoectatic, serpentine, dissecting, thrombotic, mycotic	87.5% (14/16)	100% (16/16)	81.3% (13/16)
PICA	13	Large, giant, fusiform, thrombosed, recurrent	100% (13/13)	100% (13/13)	92.3% (12/13)
Other[a]	4	Large, giant, fusiform, thrombosed	100% (4/4)	100% (4/4)	100% (4/4)
Total	40	Complex	92.5%	100%	87.5%

ACA, anterior cerebral artery; *MCA*, middle cerebral artery; *PICA*, posterior inferior cerebellar artery

[a] Other locations include the posterior cerebral artery, anterior inferior cerebellar artery, and vertebral-PICA junction

status. However, she has only left a mild hyposthenia of the lower extremity that required occasional assistance.

Discussions

Ideal anatomical site and indications for re-anastomosis bypass

In theory, ETE re-anastomosis can be performed anywhere in the cerebral circulation. However, several prerequisites, including a redundant or tortuous parent artery, a perforator-free zone surrounding anastomosis site, complete pathological wall excision, and a bridgeable gap, are required to carry out a successful bypass. As with an in situ STS bypass [51], MCA and PICA are the ideal anastomosis sites for their arterial loop and superficial surgical corridor [22]. The redundancy in the ACA and posterior cerebral artery (PCA) limits the application of ETE reconstruction in these regions and increases its failure rates if attempted [2, 21, 39]. Distally located aneurysms at non-bifurcation sites or without branches arising from the lesion also lend themselves to primary re-anastomosis [2, 21, 42, 56]. In addition, aneurysms that have one afferent and one efferent artery in fusiform morphology will make the excision and re-anastomosis bypass work elegantly [2, 4, 21, 37, 39, 42, 56]. However, as for the large and giant aneurysm, dolichoectatic dissecting aneurysms, or serpentine aneurysms, they have a limited role because the neck of such lesions can be too friable to suture and a separate ends of parent artery leaves an arterial gap unbridgeable [21, 22, 42, 56]. Thus, re-anastomosis ETE is best used for small- to medium-sized fusiform aneurysms of the MCA and PICA territories.

In the following section, we specifically reported surgical experience of re-anastomosis bypass and excision for lesions of the ACA (Fig. 1), MCA (Fig. 2), and PICA (Fig. 3) territories, as well as non-PICA arteries of the posterior circulation such as PCA-PCA, anterior inferior cerebellar artery (AICA)-AICA and VA-PICA ETE bypasses, are specifically discussed.

ACA territory re-anastomosis bypass

Unlikely the MCA and PICA, ACA has little redundancy and therefore does not allow for arterial rejoining after excision [21]. Meanwhile, the deep-seated location of the artery and the possibility of involving a perforator (recurrent artery of Heubner) further add to the difficulty of this technique.

The first ACA re-anastomosis bypass for a precallosal segment of an ACA (A3) aneurysm was reported in 1982 by Smith and Parent [48]. Subsequently, Yokoh et al. [57] carried out an ETE bypass in the management of a giant thrombosed A1-A2

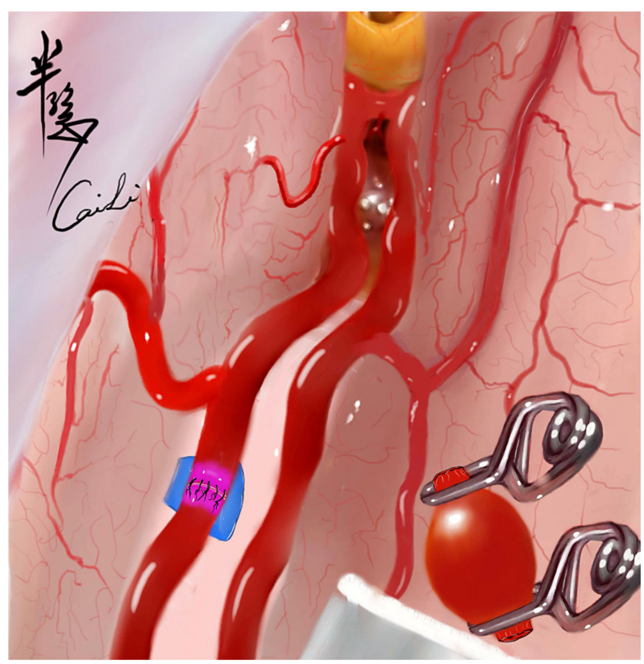

Fig. 1 An A4-A4 re-anastomosis in an ETE fashion was performed following aneurysm resection in the management of fusiform ACA aneurysm

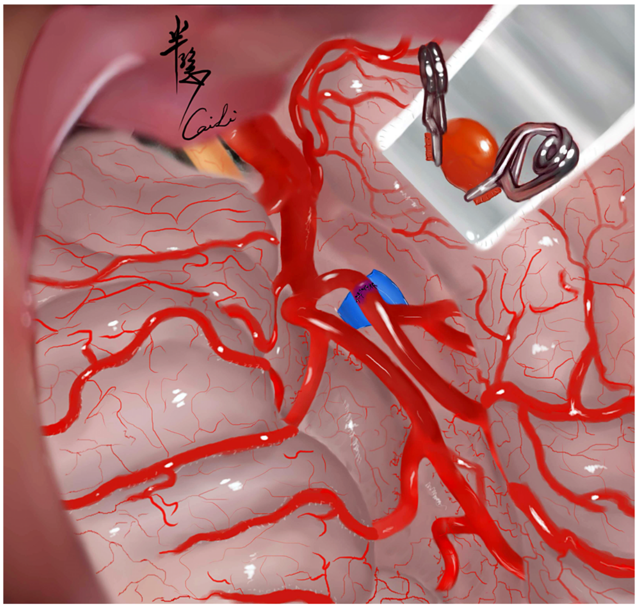

Fig. 2 The temporal M2 MCA was re-anastomosed following aneurysm resection

aneurysm. Both patients experienced unremarkable clinical outcomes, and bypass patency was detected on postoperative catheter angiography. Al-Khayat and Kopitnik [3] reported that a dissecting pericallosal artery aneurysm was excised, and both the proximal and distal ends were repaired with a re-anastomosis bypass. Postoperative angiography revealed the patent bypass status and the disappearance of the aneurysm. Matsushima et al. [26] then utilized postcommunicating infracallosal segment of ACA (A2)-callosomarginal artery (CamA) ETE anastomosis to successfully treat a giant thrombosed pericallosal artery (PerA)-CamA aneurysm. The aneurysm was ablated intraoperatively with patent status, and no neurological deficits were encountered. Nakajima et al. [30] carried out an ETE reconstruction for a patient with giant ACA aneurysm. The lesion was totally removed, and a favorable clinical outcome (mRS 0) was observed postoperatively. Hage and Charbel [14] showed a video regarding a recurrent AcomA aneurysm and then an A1-A2 re-anastomosis bypass was performed. Excellent clinical results and total obliteration of aneurysm were achieved. The only failed management case was reported by Lawton and coworkers [1, 10, 40, 42]. A thrombosed A3 aneurysm was managed using the A3-A3 re-anastomosis bypass technique following pinching off of the lesion. Although patent vessels were occluded, complete aneurysm obliteration was achieved with the same neurological status that the patient had preoperatively (mRS 4).

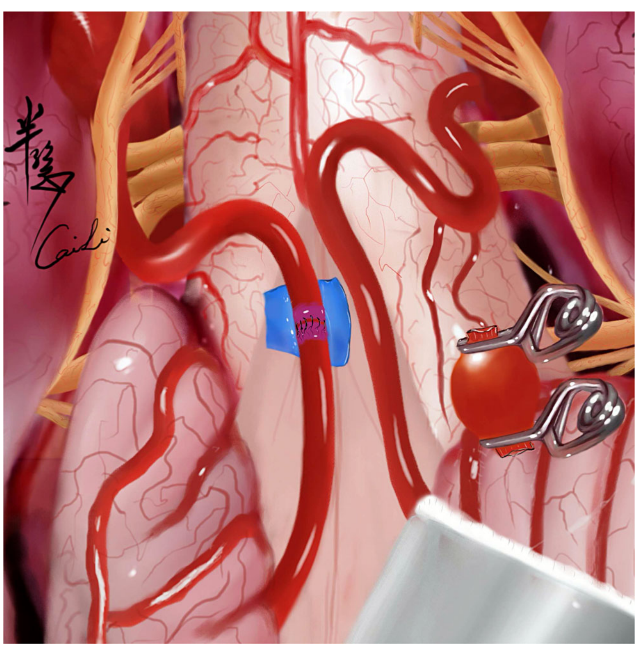

Fig. 3 An ETE re-anastomosis was performed with the resection of PICA fusiform aneurysms

Overall, seven complex ACA aneurysms were reported in the literature and treated by resection-ETE anastomosis strategy (Table 2). Six of seven patients experienced favorable outcomes. All the lesions were completely removed, and an 85.7% patency rate was observed (Table 1).

MCA territory re-anastomosis bypass

The re-anastomosis ETE anastomosis technique is the first option for aneurysms of the MCA territory [21], where three curvatures—the limen insulae for the sphenoidal segment of the MCA (M1), the insular cleft for the insular segment of the MCA (M2), and the opercular cleft for the opercular segment of the MCA (M3)—contain arteries that can be straightened to generate additional arterial length for re-anastomosis [21]. Apart from its redundant nature, superficial maneuver corridor for suturing makes MCA-MCA re-anastomosis easier. However, proximal MCA lesions might jeopardize an associated lenticulostriate with aneurysm resection.

In 1978, Dolenc [11] described the first case of successful removal of a distal fusiform MCA aneurysm that involved cortical temporal artery with ETE suture of the MCA artery (Figs. 4 and 5). The patients experienced unremarkable postoperative outcomes with total resolution of symptoms. Follow-up at 1 year revealed patent status of anastomosis site and elimination of the aneurysm. Subsequently, Anson et al. [4] reported that three cases of giant dolichoectatic aneurysms were treated by resection and re-anastomosis, and all patients experienced good recovery. Newell et al. [31] performed ETE anastomosis in the management of two insular segment aneurysms. Micro-anastomosis was aided by a jeweler and a Pierce ring-end forceps within a shorter time. Both patients experienced good recovery and patency status. Quiñones-Hinojosa and Lawton [37] reported two excision-re-anastomosis cases of MCA aneurysms. Patent bypass and obliteration of aneurysms were observed in both cases. Sanai et al. [42] recorded five cases of MCA aneurysms treated by the re-anastomosis

Table 2 List of ACA-ACA re-anastomosis bypasses for aneurysms (seven cases)

Authors [refs.]	Case No.	Aneurysm location	Aneurysm characteristics	End-to-end anastomosis site	Bypass patency	Aneurysm angiographic results	Clinical outcomes and complications
Smith and Parent [48]	1	A3 (PerA)	Giant, fusiform	A3-A3	Patent	Elimination	No neurological deficits
Yokoh et al. [57]	1	A1−A2	Giant, thrombosed	A1-A2	Patent	Elimination	Resolved visual loss and confusion
Al-Khayat and Kopitnik [3]	1	A2+A3 (PerA)	Fusiform, dissecting	A2-PerA	Patent	Elimination	Neurologically intact
Matsushima et al. [26]	1	PerA-CamA	Giant, fusiform, thrombosed	A2-CamA	Patent	Elimination	No neurological deficits
Nakajima et al. [30]	1	Distal ACA	Giant, thrombosed	A3-A3	Patent	Elimination	Favorable outcome (mRS 0)
Sanai et al.[a] [42], Rodriguez-Hernandez et al. [40], Davies and Lawton [10], and Abla and Lawton [1]	1	A3	Thrombotic, pseudoaneurysm	A3-A3	Occluded	Elimination	Unfavorable outcome (mRS 4)
Hage and Charbel [14]	1	AComA	Recurrent (previously coiled)	A1-A2	Patent	Complete obliteration	Excellent results

ACA, anterior cerebral artery; *A1*, precommunicating or horizontal segment of anterior cerebral artery; *A2*, postcommunicating infracallosal segment of anterior cerebral artery; *A3*, precallosal segment of anterior cerebral artery; *AComA*, anterior communicating artery; *CamA*, callosomarginal artery; *PerA*, pericallosal artery; *mRS*, modified Rankin scale

[a] The final mRS score was the same as the preoperative value

procedure, and four patent bypasses were achieved. Seo et al. [45] utilized excision and re-anastomosis techniques to treat two cases of ruptured fusiform MCA aneurysms. Although one patient died due to the initial injury of SAH, another patient experienced intact neurological function and good patency of the bypass site. Pavesi et al. [36] treated a giant thrombosed serpentine aneurysm with an ETE M1-temporal M2 bypass procedure. Complete disappearance of the lesion was confirmed by cerebral angiogram. However, fronto-insular ischemia was detected postoperatively and encountered hyposthenia of the left lower extremity (GOS 4). Meybodi et al. [28] reported six cases of excision-re-anastomosis strategy for complex MCA aneurysm management. This case series included two cases each of M1-M1 and M2-M2 and three

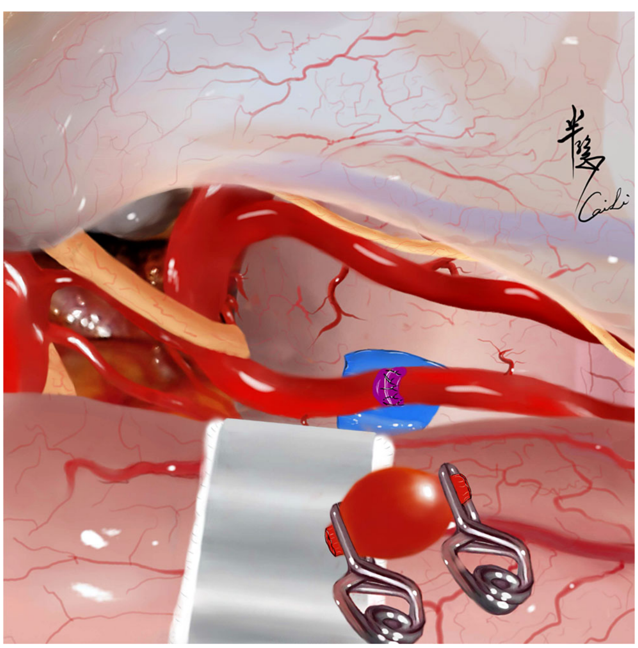

Fig. 4 A fusiform aneurysm of P2 was amputated followed by re-anastomosis technique

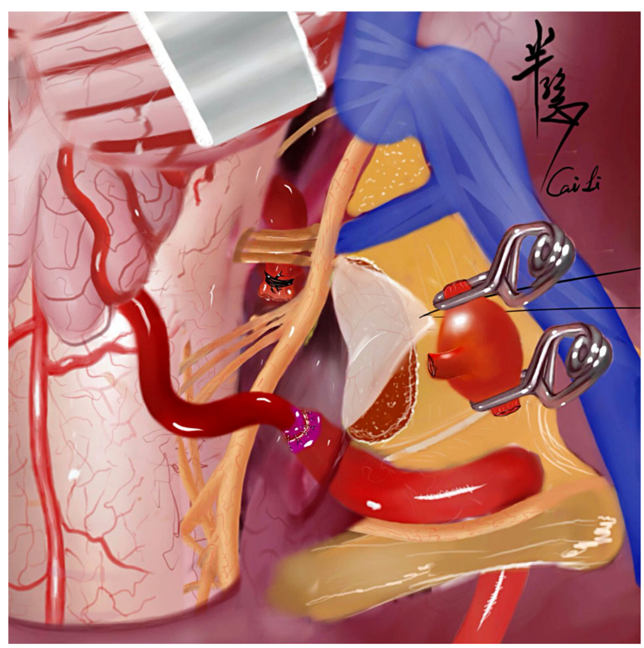

Fig. 5 The VA-PICA junction aneurysm was resected and distal VA was anastomosed to the PICA with the sacrifice of proximal VA

cases of M3-M3 re-anastomosis bypass following aneurysm excision. Five of six patients experienced favorable outcomes, and the postoperative angiogram illustrated 66.7% of the bypass patency rate. Subsequently, several case reports of aneurysmal excision-re-anastomosis have been published by Schönmayr and Zierski [43], Laborde et al. [20], Miyagi et al. [29], Ceylan et al. [7], and Xu et al. [56]. The undisturbed patency and elimination of the aneurysm were observed postoperatively. In addition, several publications have illustrated such techniques in surgical video (Table 3) [39, 47].

In total, 16 cases of MCA complex aneurysms were treated by re-anastomosis ETE bypass with comprehensive descriptions of the medical records and surgical outcomes. Thirteen cases were recovered without neurological deficits and 87.5% of the bypasses were patent (Table 1).

PICA territory re-anastomosis bypass

In the territory of PICA, the re-anastomosis technique is preferable to other types of bypass methods, especially the tonsillomedullary segment of the PICA (p3) for less-vulnerable cranial nerves, few perforators, and excellent exposure [6, 21]. Like MCA, the PICA has three curved vessel loops that straighten easily for additional length and mobility. A first loop that unofficially defined is located between the anterior medullary (p1) and lateral medullary segments (p2) of PICA. Another two official loops are the caudal loop of p3 and the cranial loop of the telovelotonsillar segment of PICA (p4) [21]. However, others have considered PICA re-anastomosis to be less than straightforward, and increased technical difficulty is associated with the depth, proximity to the medullary

Table 3 List of previous MCA-MCA re-anastomosis bypasses for aneurysms (24 cases)

Author [refs.]	Case No.	Aneurysm location	Aneurysm characteristics	ETE anastomosis site	Bypass patency	Aneurysm angiographic results	Clinical outcomes and complications
Dolenc [11]	1	M4	Fusiform	M4-M4	Patent	Elimination	No neurological deficits
Schonmayr and Zierski [43]	1	MCA	Giant, thrombosed	MCA-MCA	Patent	Elimination	Uneventful course
Laborde et al. [20]	1	MCA	Giant	MCA-MCA	Patent	Elimination	Dead (GOS 1)
Miyagi et al. [29]	1	M2	Giant, thrombosed	M2-M2	Patent	Elimination	Uneventful course
Anson et al. [4]	3	MCA	Giant, dolichoectatic	MCA-MCA	NA	NA	Favorable outcome (GOS 0–2)[a]
Ceylan et al. [7]	1	M2	Giant, fusiform, thrombosed	M2-M2	Patent	Elimination	No neurological deficits
Newell et al. [31]	2	M2	Large, fusiform, thrombosed	M2-M2	Patent	Elimination	Good recovery
Quinones-Hinojosa and Lawton [37][b]	2	MCA	Fusiform/dolichoectatic, mycotic	MCA-MCA	Patent	Elimination	No adverse complications
Sanai et al. [42][b]	5	MCA	NA	MCA-MCA	80% (4/5)	Elimination	NA
Seo et al. [45]	2	ATA; M3	Fusiform; giant, fusiform	ATA-ATA; M2-M3	Patent; NA	NA	Excellent outcome (GOS 5); death (GOS 1)
Rodriguez-Hernandez et al. [40][b]	3	Distal MCA	NA	NA	NA	NA	NA
Davies and Lawton [10][b]	9	MCA	NA	MCA-MCA	NA	NA	NA
Rodriguez-Hernandez and Lawton [39][b]	1	M1-M2	Giant, serpentine, thrombosed	M1-M2	Patent	Elimination	NA
Pavesi et al. [36]	1	M1-M2	Giant, thrombosed, serpentine	M1-temporal M2	Patent	Elimination	Mild hyposthenia (GOS 4)
Singh et al. [47]	1	M2	Large, fusiform, thrombosed	M2-M2	Patent	Elimination	Complete recovery
Meybodi et al. [28][b]	6	M1 (2); M3 (4)	Complex[d]	M1-M1 (2); M2-M2 (1); M3-M3 (3)	66.7% (4/6)	Elimination	Favorable (mRS 0–1) (5); unfavorable (mRS 3) (1)
Xu et al. [56]	1	M2	Giant, fusiform	M2-M2	Patent	Elimination	mRS 0

GOS, Glasgow outcome scale; *MCA*, middle cerebral artery; *M1*, sphenoidal segment of middle cerebral artery; *M2*, insular segment of middle cerebral artery; *M3*, opercular segment of middle cerebral artery; *mRS*, modified Rankin scale; *NA*, not available

[a] The GOS score of 1 is a good recovery, 2 is moderate disability, 3 is severe disability, 4 is vegetative, and 5 is dead

[b] Total number of cases by Lawton and coworkers [1, 3, 15, 17, 19, 33] were calculated by the publication in 2014

[d] Complex aneurysms were featured by giant size, mycotic pathogenesis, or thrombosed, serpentine, dolichoectatic shape

perforators, retraction of both tonsils for exposure, and limited surgical freedom [21, 46].

Dolenc [12] reported the first case of excision-reconstruction technique for PICA aneurysm treatment with patent bypass. Quiñones-Hinojosa and Lawton [37] then treated two fusiform/dolichoectatic PICA aneurysms. Both lesions were resected intraoperatively, and ETE anastomosis was then performed. Postoperative outcomes were uneventful with patent bypass status. Sanai et al. [42] described five other PICA aneurysms that were resolved by this technique, and all bypasses were patent. Kalani et al. [18] described three cases of PICA aneurysms treated by ETE re-vascularization. Complete obliteration of the lesion and patent bypass were achieved in two patients, and the third died for the sake of vessel occlusion. Abla et al. [2] reported the largest case series comprised 13 PICA-PICA re-anastomosis reconstructions. All aneurysms were excised intraoperatively. Bypass occlusion and ischemic complications were not observed. Bonda et al. [6] described two cases of p2 fusiform aneurysms that were resected followed by the re-anastomosis technique. Both patients experienced favorable outcomes (mRS 0–1), and patent bypass was confirmed by postoperative angiography. Multiple case reports or surgical videos in the management of complex intracranial aneurysms have been described in the literature by

Table 4 Listing of previous PICA-PICA re-anastomosis bypasses for aneurysms (31 cases)

Author [refs.]	Case No.	Aneurysm location	Aneurysm characteristics	End-to-end anastomosis site	Bypass patency	Aneurysm angiographic results	Clinical outcomes and complications
Dolenc [12]	1	PICA	Large, fusiform ectasia	PICA-PICA	Patent	Elimination	Neurologically intact
Samii and Turel [41]	1	PICA	Large, fusiform	PICA-PICA	Patent	Elimination	Favorable outcome
Laborde et al. [20]	1	PICA	Giant	PICA-PICA	Patent	Elimination	Unfavorable outcome (GOS 2)
Madsen and Heros [24]	1	p3	Giant	p3-p3	NA	Elimination	Neurologically intact
Ikeda et al. [17]	1	Distal PICA	Fusiform	p2	Patent	Elimination	Excellent outcome
Anson et al. [4]	1	PICA	Giant, fusiform	PICA-PICA	NA	NA	Favorable outcome (GOS 1)[a]
Hamada et al. [15]	1	p4 (choroidal point)	Giant, thrombosed	p4-p4	Patent	Elimination	Satisfactory outcome
Sekhar and Kalavakonda [44]	1	p3	Fusiform	p3-p3	Patent	Elimination	NA
Nussbaum et al. [33]	1	PICA	Fusiform	PICA-PICA	Patent	Elimination	Good outcome
Evans et al. [13]	1	Distal PICA	Fusiform	PICA-PICA	Patent	Elimination	Good recovery (KPS 90)
Quinones-Hinojosa and Lawton [37][b]	2	PICA	Fusiform/ dolichoectatic	PICA-PICA	Patent	Elimination	No adverse complications
Sanai et al. [42][b]	5	MCA	NA	MCA-MCA	Patent	Elimination	NA
Lim et al. [23]	1	p2	Dissecting	p2-p2	Patent	Elimination	Excellent
Rodriguez-Hernandez et al. [40][b]	6	p2-p3	NA	PICA-PICA	NA	NA	NA
Davies and Lawton [10][b]	10	NA	NA	PICA-PICA	NA	NA	NA
Rodriguez-Hernandez and Lawton [39][b]	1	p3	Giant, thrombosed	p3-p3	Patent	Elimination	NA
Kalani et al. [18]	3	PICA	Dissecting (1), saccular (2)	PICA-PICA	33.3% (1/3) patent	Obliterated (2); NA (1)	Died (1); NA (2)
Mascitelli et al. [25]	1	p3 (caudal loop)	Pre-coiled	p3-p3	Patent	Elimination	Neurologically intact
Abla et al. [2][b]	13	PICA	NA	PICA-PICA	Patent	Elimination	NA
Silva et al. [46]	1	PICA	NA	PICA-PICA	Patent	Elimination	Favorable outcome (mRS 1)
Bonda et al. [6]	2	p2	Fusiform	p2-p2	Patent	Elimination	Favorable outcome (mRS 0–1)

GOS, Glasgow outcome scale; *KPS*, Karnofsky performance scale; *mRS*, modified Rankin scale; *PICA*, posterior inferior cerebellar artery; *p2*, lateral medullary segment of PICA, from the inferior olive to the origins of the lower cranial nerves at the lateral edge of the olive; *p3*, tonsillomedullary segment of PICA including caudal loop; *p4*, telovelotonsillar segment of PICA; *VA*, vertebral artery

[a] A GOS score of 1 is a good recovery, 2 is moderate disability, 3 is severe disability, 4 is vegetative, and 5 is dead

[b] The total number of cases reported by Lawton and coworkers [1, 3, 15, 17, 19, 33] was calculated from the latest publication

Samii and Turel [41], Laborde et al. [20], Madsen and Heros [24], Ikeda et al. [17], Anson et al. [4], Hamada et al. [15], Sekhar and Chandrasekar [44], Nussbaum et al. [33], Evans et al. [13], Lim et al. [23], Rodriguez-Hernandez and Lawton [39], Mascitelli et al. [25], and Silva et al. [46]. All aneurysms were removed from the circulation with patent bypass status. A smooth postoperative course was observed except that one patient died due to the pulmonary embolus and another patient experienced with GOS 2 (Table 4).

A total of 13 cases of complex PICA aneurysms were analyzed with comprehensive descriptions of the medical records and surgical outcomes, and a 100% patency rate was recorded. Although one patient encountered surgical-related complications, all the lesions were completely obliterated from the circulation (Table 1).

Touho [49] described the only case of using the PICA-PICA re-anastomosis technique for a clivus and foramen magnum meningioma resection. The tumor was totally removed following a part of the lateral medullary segment of the PICA incision and ETE reconstruction. Postoperative outcome was favorable without meningioma recurrence in the following 2-year follow-up.

Non-PICA territory re-anastomosis bypass of posterior circulation

PCA-PCA and AICA-AICA re-anastomosis bypass

Re-anastomosis is possible, but the courses of the PCA and AICA have little redundancy or tortuosity and are therefore difficult to reconnect after an aneurysmal segment has been excised [21].

The only case of re-anastomosis ETE bypass in the territory of the PCA was reported by Chang et al. [8, 9]. The postcommunicating segment of the posterior cerebral artery (P2) aneurysm was resected, and the bilateral ends of the parent arteries were re-approximated to each other to reconstruct normal PCA circulation. Postoperative angiography revealed patent PCA and the patient discharged with intact neurological function.

Hoh et al. [16] utilized excision and primary re-anastomosis methods to treat a fusiform AICA aneurysm. The patency status and outcome of aneurysm were not described, but the patient experienced good recovery (GOS 5) postoperatively. Another AICA-AICA ETE reconstruction was reported by Pasler et al. [35]. The aneurysms that mimicked a vestibular schwannoma were excised via a retrosigmoid approach, and the vessel stumps were re-anastomosed to each other. Postoperative outcome was uneventful with patency of bypass.

VA-PICA re-anastomosis bypass

When the lesion involves the vertebral artery (VA) and PICA origin, re-anastomosis of the VA-anterior medullary segment of the PICA (p1) is a viable choice. Several limitations that have been described may produce technical challenges such as caliber mismatch, constraints of the operative field, injury of the lower cranial nerve and perforators, forced mobilization of PICA, and the procedure is more technically challenging [5, 31, 34]. However, the caliber mismatch between VA and PICA has been overcome with an oblique cut in PICA to lengthen its circumference [5], and excellent patency rates associated such restorative technique have been recorded in the articles [21].

Benes et al. [5] reported that a VA-PICA junction aneurysm was treated by resection and ETE bypass. The thrombosed lesion was removed to release brainstem compression following proximal VA-to-p1 anastomosis. Good filling of the anastomosed PICA was observed, and the patient experienced intact neurological function except for the minor swallowing malfunction. Ogasawara et al. [34] reported another case of VA-P1 re-anastomosis. The proximal stump of PICA was anastomosed ETE to the VA followed by the vertebral/p1

Table 5 List of previous non-PICA-PICA re-anastomosis for posterior circulation aneurysms

Author [refs.]	Case No.	Aneurysm location	Aneurysm characteristics	End-to-end anastomosis site	Bypass patency	Aneurysm angiographic results	Clinical outcomes and complications
Chang et al. [8, 9]	1	P2	Fusiform	P2-P2	Patent	Elimination	Neurologically intact
Hoh et al. [16]	1	AICA	Fusiform	AICA-AICA	NA	NA	Good recovery (GOS 5)
Benes et al. [5]	1	V4-p1 junction	Giant, thrombosed	Proximal VA-p1	Patent	Elimination	Neurological intact except minor swallowing dysfunction
Ogasawara et al. [34]	1	V4-p1 junction	Large	VA-PICA	Patent	Elimination	Mild transient dysphagia
Pasler et al. [35]	1	AICA	Fusiform, thrombosed	AICA-AICA	Patent	Elimination	Complete recovery
Abla et al. [2]	1	V4-p1 junction	NA	VA-PICA	Occlusion	Elimination	NA

AICA, anterior inferior cerebellar artery; *GOS*, Glasgow outcome scale; *NA*, not applicable; *p1*, anterior medullary segment of posterior inferior cerebellar artery; *p2*, postcommunicating segment of posterior cerebral artery; *V4*, intracranial segment of vertebral artery junction excision. Patent bypass was revealed on postoperative catheterization, but the patient encountered mild dysphagia due to nerve palsy. Abla et al. [2] performed a V4-PICA re-anastomosis, and bypass occlusion was encountered due to the mismatch in caliber between the VA and PICA.

Of all four cases in the non-PICA territory posterior circulation with comprehensive descriptions of the medical records and surgical outcomes (Table 5), all the patients experienced favorable outcomes and a 100% aneurysm obliteration and bypass patency rate were observed (Table 1).

Conclusions

End-to-end re-anastomosis remains a simple modality in the microsurgical bypass armamentarium. Safe and effective surgical outcomes can be achieved in select cases that rarely involve perforators and branches.

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Compliance with ethical standards

Conflict of interest None.

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Abla AA, Lawton MT (2014) Anterior cerebral artery bypass for complex aneurysms: an experience with intracranial-intracranial reconstruction and review of bypass options. J Neurosurg 120:1364–1377. https://doi.org/10.3171/2014.3.jns132219
2. Abla AA, McDougall CM, Breshears JD, Lawton MT (2016) Intracranial-to-intracranial bypass for posterior inferior cerebellar artery aneurysms: options, technical challenges, and results in 35 patients. J Neurosurg 124:1275–1286. https://doi.org/10.3171/2015.5.jns15368
3. Al-Khayat H, Kopitnik TA (2004) Primary end-to-end anastomosis of anterior cerebral artery dissecting aneurysm: technical case report and review of the literature. Neurosurgery 55:E449–E454. https://doi.org/10.1227/01.neu.0000130039.76769.60
4. Anson JA, Lawton MT, Spetzler RF (1996) Characteristics and surgical treatment of dolichoectatic and fusiform aneurysms. J Neurosurg 84:185–193. https://doi.org/10.3171/jns.1996.84.2.0185
5. Benes L, Kappus C, Sure U, Bertalanffy H (2006) Treatment of a partially thrombosed giant aneurysm of the vertebral artery by aneurysm trapping and direct vertebral artery-posterior inferior cerebellar artery end-to-end anastomosis: technical case report. Oper Neurosurg 59:ONSE166–ONSE167. https://doi.org/10.1227/01.neu.0000220034.08995.37
6. Bonda DJ, Labib M, Katz JM, Ortiz RA, Chalif D, Setton A, Langer DJ, Dehdashti AR (2017) Intracranial bypass of posterior inferior cerebellar artery aneurysms: indications, technical aspects, and clinical outcomes. Oper Neurosurg 13:586–595. https://doi.org/10.1093/ons/opx064
7. Ceylan S, Karakuş A, Duru S, Baykal S, İlbay K (1998) Reconstruction of the middle cerebral artery after excision of a giant fusiform aneurysm. Neurosurg Rev 21:189–193. https://doi.org/10.1007/bf02389331
8. Chang HS, Fukushima T, Miyazaki S, Tamagawa T (1986) Fusiform posterior cerebral artery aneurysm treated with excision and end-to-end anastomosis. J Neurosurg 64:501–504. https://doi.org/10.3171/jns.1986.64.3.0501
9. Chang HS, Fukushima T, Takakura K, Shimizu T (1986) Aneurysms of the posterior cerebral artery: report of ten cases. Neurosurgery 19:1006–1011. https://doi.org/10.1227/00006123-198612000-00017
10. Davies JM, Lawton MT (2014) Advances in open microsurgery for cerebral aneurysms. Neurosurgery 74:S7–S16. https://doi.org/10.1227/neu.0000000000000193
11. Dolenc V (1978) Treatment of fusiform aneurysms of the peripheral cerebral arteries. J Neurosurg 49:272–277. https://doi.org/10.3171/jns.1978.49.2.0272
12. Dolenc V (1982) End-to-end suture of the posterior inferior cerebellar artery after the excision of a large aneurysm: case report. Neurosurgery 11:690–693. https://doi.org/10.1227/00006123-198211000-00014
13. Evans JJ, Sekhar LN, Rak R, Stimac D (2004) Bypass grafting and revascularization in the management of posterior circulation aneurysms. Neurosurgery 55:1036–1049. https://doi.org/10.1227/01.neu.0000140822.64362.c6
14. Hage ZA, Charbel FT (2015) Clipping of a ruptured anterior communicating artery aneurysm with right A1–A2 sectioning and reanastomosis. Neurosurg Focus 39:V10. https://doi.org/10.3171/2015.7.focusvid.14602
15. Hamada J-I, Nagahiro S, Mimata C, Kaku T, Ushio Y (1996) Reconstruction of the posterior inferior cerebellar artery in the treatment of giant aneurysms. J Neurosurg 85:496–499. https://doi.org/10.3171/jns.1996.85.3.0496
16. Hoh BL, Putman CM, Budzik RF, Carter BS, Ogilvy CS (2001) Combined surgical and endovascular techniques of flow alteration to treat fusiform and complex wide-necked intracranial aneurysms that are unsuitable for clipping or coil embolization. J Neurosurg 95:24–35. https://doi.org/10.3171/jns.2001.95.1.0024
17. Ikeda A, Yamaguchi T, Yamaguchi T, Yamamoto I, Sato O (1991) Excision and end-to-end anastomosis of a fusiform aneurysm of the distal posterior inferior cerebellar artery associated with ischemia. Neurol Med Chir 31:351–355. https://doi.org/10.2176/nmc.31.351
18. Kalani MYS, Ramey W, Albuquerque FC, McDougall CG, Nakaji P, Zabramski JM, Spetzler RF (2014) Revascularization and aneurysm surgery. Neurosurgery 74:482–497. https://doi.org/10.1227/neu.0000000000000312
19. Kawashima M, Rhoton AL, Tanriover N, Ulm AJ, Yasuda A, Fujii K (2005) Microsurgical anatomy of cerebral revascularization. Part II: posterior circulation. J Neurosurg 102:132–147. https://doi.org/10.3171/jns.2005.102.1.0132
20. Laborde G, Gilsbach J, Harders A (1988) The microvascular Doppler—an intraoperative tool for the treatment of large and giant aneurysms. In: Proceedings of the 8th European congress of neurosurgery, Barcelona. Springer, Vienna, pp 75–80
21. Lawton MT (2018) Seven bypasses: tenets and techniques for revascularization. Thieme Verlag, Stuttgart, Germany
22. Lawton MT, Spetzler RF (1999) Surgical strategies for giant intracranial aneurysms. In: Langmoen IA, Lundar T, Aaslid R, Reulen

HJ (eds) Neurosurgical management of aneurysmal subarachnoid haemorrhage. Springer, Vienna, pp 141–156
23. Lim SM, Choi IS, Hum BA, David CA (2010) Dissecting aneurysms of the distal segment of the posterior inferior cerebellar arteries: clinical presentation and management. AJNR Am J Neuroradiol 31:1118–1122. https://doi.org/10.3174/ajnr.a2014
24. Madsen JR, Heros RC (1988) Giant peripheral aneurysm of the posterior inferior cerebellar artery treated with excision and end-to-end anastomosis. Surg Neurol 30:140–143. https://doi.org/10.1016/0090-3019(88)90100-0
25. Mascitelli JR, Ben-Haim S, Paramasivam S, Zarzour HK, Rothrock RJ, Bederson JB (2015) Association of a distal intradural-extracranial posterior inferior cerebellar artery aneurysm with chiari type I malformation. Neurosurgery 77:E660–E665. https://doi.org/10.1227/neu.0000000000000870
26. Matsushima K, Kawashima M, Suzuyama K, Takase Y, Takao T, Matsushima T (2011) Thrombosed giant aneurysm of the distal anterior cerebral artery treated with aneurysm resection and proximal pericallosal artery-callosomarginal artery end-to-end anastomosis: case report and review of the literature. Surg Neurol Int 2: 135. https://doi.org/10.4103/2152-7806.85608
27. Meybodi AT, Deng H, Benet A, Lawton MT (2018) Intracranial-intracranial bypass. Contemp Neurosurg 40:1–8. https://doi.org/10.1097/01.cne.0000530871.39106.b4
28. Meybodi AT, Huang W, Benet A, Kola O, Lawton MT (2017) Bypass surgery for complex middle cerebral artery aneurysms: an algorithmic approach to revascularization. J Neurosurg 127:463–479. https://doi.org/10.3171/2016.7.jns16772
29. Miyagi J, Shigemori M, Sugita Y, Nishio N, Harada K, Kuramoto S (1991) Giant aneurysm of the middle cerebral artery presenting with complex partial seizure. Neurol Med Chir 31:953–956. https://doi.org/10.2176/nmc.31.953
30. Nakajima H, Kamiyama H, Nakamura T, Takizawa K, Ohata K (2013) Direct surgical treatment of giant intracranial aneurysms on the anterior communicating artery or anterior cerebral artery. Neurol Med Chir 53:153–156. https://doi.org/10.2176/nmc.53.153
31. Newell DW, Schuster JM, Avellino AM (2002) Intracranial-to-intracranial vascular anastomosis created using a microanastomotic device for the treatment of distal middle cerebral artery aneurysms. J Neurosurg 97:486–491. https://doi.org/10.3171/jns.2002.97.2.0486
32. Nossek E, Langer DJ (2018) Internal maxillary artery to middle cerebral artery cranial bypass: the new "work horse" for cerebral flow replacement. World Neurosurg 115:44–46. https://doi.org/10.1016/j.wneu.2018.03.214
33. Nussbaum ES, Mendez A, Camarata P, Sebring L (2003) Surgical management of fusiform aneurysms of the peripheral posteroinferior cerebellar artery. Neurosurgery 53:831–835. https://doi.org/10.1227/01.neu.0000084162.29616.43
34. Ogasawara K, Kubo Y, Tomitsuka N, Sasoh M, Otawara Y, Arai H, Ogawa A (2006) Treatment of vertebral artery aneurysms with transposition of the posterior inferior cerebellar artery to the vertebral artery combined with parent artery occlusion. J Neurosurg 105: 781–784. https://doi.org/10.3171/jns.2006.105.5.781
35. Päsler D, Baldauf J, Runge U, Schroeder HWS (2011) Intrameatal thrombosed anterior inferior cerebellar artery aneurysm mimicking a vestibular schwannoma. J Neurosurg 114:1057–1060. https://doi.org/10.3171/2010.9.jns10491
36. Pavesi G, Dimitriadis S, Baroni S, Vallone S, Valzania F, Costella GB, Feletti A (2015) Intraoperative functional and perfusion monitoring during surgery for giant serpentine middle cerebral artery aneurysms. World Neurosurg 84:592.e515–592.e521. https://doi.org/10.1016/j.wneu.2015.03.014
37. Quiñones-Hinojosa A, Lawton MT (2005) In situ bypass in the management of complex intracranial aneurysms: technique application in 13 patients. Oper Neurosurg 57:140–145. https://doi.org/10.1227/01.neu.0000163599.78896.f4
38. Rahme R, Alimi M, Sudhakar TD, Langer DJ (2018) Management of complex intracranial aneurysms: principles of microsurgical deconstruction and cerebrovascular bypass. Intracranial Aneurysms. https://doi.org/10.1016/B978-0-12-811740-8.00015-0
39. Rodríguez-Hernández A, Lawton MT (2014) End-to-end reanastomosis technique for fusiform aneurysms. Oper Neurosurg 10:157; discussion 157–158–158. https://doi.org/10.1227/neu.0000000000000124
40. Rodríguez-Hernández A, Zador Z, Rodríguez-Mena R, Lawton MT (2013) Distal aneurysms of intracranial arteries: application of numerical nomenclature, predilection for cerebellar arteries, and results of surgical management. World Neurosurg 80:103–112. https://doi.org/10.1016/j.wneu.2012.09.010
41. Samii M, Turel KE (1985) Possibility of the excision of aneurysms in the vertebrobasilar system followed by end-to-end anastomosis for the maintenance of circulation. Neurol Res 7:39–45. https://doi.org/10.1080/01616412.1985.11739699
42. Sanai N, Zador Z, Lawton MT (2009) Bypass surgery for complex brain aneurysms. Neurosurgery 65:670–683; discussion 683. https://doi.org/10.1227/01.neu.0000348557.11968.f1
43. Schönmayr R, Zierski J (1983) Middle cerebral artery revascularisation. Neurosurg Rev 6:25–28. https://doi.org/10.1007/bf01742982
44. Sekhar LN, Kalavakonda C (2002) Cerebral revascularization for aneurysms and tumors. Neurosurgery 50:321–331. https://doi.org/10.1227/00006123-200202000-00014
45. Seo B-R, Kim T-S, Joo S-P, Lee J-M, Jang J-W, Lee JK, Kim JH, Kim SH (2009) Surgical strategies using cerebral revascularization in complex middle cerebral artery aneurysms. Clin Neurol Neurosurg 111:670–675. https://doi.org/10.1016/j.clineuro.2009.06.002
46. Silva MA, See AP, Aziz-Sultan MA, Patel NJ (2017) Surgical treatment of a double origin posterior inferior cerebellar artery aneurysm and insights from embryology: case report and literature review. Oper Neurosurg 13:E8–E12. https://doi.org/10.1093/ons/opx002
47. Singh H, da Silva HB, Straus DC, Zeinalizadeh M, Sekhar LN (2017) Microsurgical management of large, fusiform, partially thrombosed middle cerebral artery (M2) aneurysm with end-to-end M2 anastomosis: 3-dimensional operative video. Oper Neurosurg 13:535. https://doi.org/10.1093/ons/opx008
48. Smith RR, Parent AD (1982) End-to-end anastomosis of the anterior cerebral artery after excision of a giant aneurysm. J Neurosurg 56:577–580. https://doi.org/10.3171/jns.1982.56.4.0577
49. Touho H (1999) End-to-end anastomosis of the posterior inferior cerebellar artery before excision of a meningioma involving the lower clivus and the foramen magnum. Surg Neurol 52:185–188. https://doi.org/10.1016/s0090-3019(99)00067-1
50. Wang L, Cai L, Lu S, Qian H, Lawton MT, Shi X (2018) The history and evolution of internal maxillary artery bypass. World Neurosurg 113:320–332. https://doi.org/10.1016/j.wneu.2018.02.158
51. Wang L, Cai L, Qian H, Lawton MT, Shi X (2018) The in situ side-to-side bypass technique: a comprehensive review of the technical characteristics, current anastomosis approaches, and surgical experience. World Neurosurg 115:357–372. https://doi.org/10.1016/j.wneu.2018.04.173
52. Wang L, Lu S, Qian H, Shi X (2017) Internal maxillary artery bypass with radial artery graft treatment of giant intracranial aneurysms. World Neurosurg 105:568–584. https://doi.org/10.1016/j.wneu.2017.06.014
53. Wang L, Lu S, Qian H, Shi X (2017) Internal maxillary bypass for complex pediatric aneurysms. World Neurosurg 103:395–403. https://doi.org/10.1016/j.wneu.2017.04.055

54. Wang L, Shi X, Liu F, Qian H (2016) Bypass surgery to treat symptomatic fusiform dilation of the internal carotid artery following craniopharyngioma resection: report of 2 cases. Neurosurg Focus 41:E17. https://doi.org/10.3171/2016.9.focus16252
55. Wang L, Shi X, Qian H (2017) Flow reversal bypass surgery: a treatment option for giant serpentine and dolichoectatic aneurysms—internal maxillary artery bypass with an interposed radial artery graft followed by parent artery occlusion. Neurosurg Rev 40: 319–328. https://doi.org/10.1007/s10143-016-0778-8
56. Xu F, Xu B, Huang L, Xiong J, Gu Y, Lawton MT (2018) Surgical treatment of large or giant fusiform middle cerebral artery aneurysms: a case series. World Neurosurg 115:e252–e262. https://doi.org/10.1016/j.wneu.2018.04.031
57. Yokoh A, Ausman JI, Dujovny M, Diaz FG, Berman SK, Sanders J, Mirchandani HG (1986) Anterior cerebral artery reconstruction. Neurosurgery 19:26–35. https://doi.org/10.1097/00006123-198607000-00004